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TOOL ENGINEERING

ANALYSIS AND PROCEDURE

By

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Dedicated to the Memory of
My Father

WILLIAM JAY DOYLE

PREFACE

Engineering of any sort is essentially an endeavor to solve problems. Tool engineering deals with the solution of problems that arise in planning and tooling for production. It was far advanced as an art before engineering techniques were applied to it. As a result, tool engineering depends upon many empirical solutions to its problems, and an acquaintance with them is necessary to expedite work in the field. One aim of this book is to present the important procedures of tool engineering. In addition, the intention is to go further by explaining the reasons for the procedures and showing how problems of tool engineering may be solved more exactly by analytical methods based upon engineering fundamentals.

During a period of about 15 years in industry, the author became interested in developing more concise concepts and effectiveness for the principles of tool engineering. Consequently, he returned to the atmosphere of the university to try to correlate the practical aspects with the theoretical. From that study has come the substance of this text and the course for which it is used.

It is the opinion of many engineers that the analytical approach offers means of presenting this subject more significantly and cogently than an entirely descriptive approach. Although intended primarily for a college course, this text should be of value to others. Many graduate engineers today are engaged in tool engineering. This book can help them to make the most of their training in their pursuit of tool engineering. Many men rise to tool engineering from the ranks of industry. Often they find it necessary to supplement their intimate grasp of industrial practices with a study of academic subjects. To them, this book should give valuable insight into engineering methods of analysis and reasoning.

The author wishes to acknowledge the encouragement and guidance given in this work by Professor N. A. Parker, Head of the Department of Mechanical Engineering, and Professor C. H. Casberg,

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The author is indebted particularly to Dr. B. T. Chao for his painstaking review and criticism of many of the topics of this text.

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No treatment of the subject of tool engineering would be possible without the generous cooperation of the manufacturers of tools and machines. It is fitting that the contribution of each be acknowledged where it appears, as is done throughout the text.

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1 THE NATURE AND SCOPE OF TOOL ENGINEERING

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Definition of tool engineering

It is not easy to define the scope of the term "tool engineering" with precision. Tool engineering is an expanding field, and there is valid reason for lack of agreement on the inclusion of certain activities within the "tool engineering" classification. The following definitions by prominent tool engineers are as authoritative as any:

1. "The Tool Engineer's function is to provide the machines and tools to produce the product engineer's design." (Grant S. Wilcox, Jr., "The Function of the Tool Engineer," *Tool Engineer*, May 1946, p. 38.)

2. "The Tool Engineer is a specialist in the design and application of tools, jigs, fixtures, and other manufacturing equipment, which are important factors in determining the cost of the end product." (C. E. J. Brickner, "The Tool Engineer's Place in Industry," *Tool Engineer*, July 1946, p. 37.)

3. "Determining the method of manufacture, the sequence and character of the operations involved, the time involved in each operation and its cost, the general nature of the equipment required and the fashion in which all this fits into the industrial process and plant as a whole comprises the planning stage of tool engineering. It might be added that this is possibly the most important and characteristic step in the whole tool engineering process.

"Proper and thorough planning may spell the difference between profit or loss on the finished product. The efficient manufacturing process or tooling up job cannot be accomplished without competent and thorough planning. To accomplish this requires decision and judgment that is acquired only by experience and a comprehensive knowledge of the subject. In this phase of tool engineering activity is included the selection of the equipment required and its basic design." (O. W. Winter, "The Tool Engineer Defined," *Tool Engineer*, August 1945, p. 46.)

4. "Tool Engineering includes the analyses, planning, design, construction and application of any one or all of the following, whether they be used for toolroom, job shop, semi-production or mass production work:
    a. Cutting tools, tool-holders, and cutting fluids.
    b. Machine tools, particularly those of special types.

c. Jigs and fixtures for machining.
d. Gages and measuring instruments.
e. Dies for sheet metal.
f. Dies for forging, upsetting, cold finishing, extrusion.
g. Dies for molding, die castings.
h. Patterns for permanent molds.
i. Fixtures and accessories for welding, riveting and assembling.
j. Abrasives, grinding compounds and fixtures for grinding, honing, and finishing.

"A tool engineer is probably interested in only one, or at the most a few of these items, as in high quality manufacturing specialists are required. Each one of these subjects is being improved and expanded constantly as a result of practice and research." (This last section is from a resume of a paper by O. W. Boston, Professor of Metal Processing and Department Chairman, University of Michigan, presented at the *ASTE* New Era Exposition, Cleveland, Ohio, Spring 1946.)

The background of tool engineering

The tool engineer is a comparative newcomer to the industrial world. Men living today can recall the time when tool engineering, as it now exists, was unknown. That does not mean that under such conditions tooling activity did not exist since machinery and tools are a necessity of any manufacturing system. It does mean that new ideas and approaches have been applied to the problems of tooling for industry.

Tool engineering is one of the aspects of a general movement characterized by the analytical or "scientific" method of attacking industrial problems and variously known under such names as "scientific management," "efficiency engineering," or others. Until about the beginning of the present century the design, organization, and conduct of industrial enterprise was entirely an empirical art. Under such conditions the tooling function was assumed by the shop supervisors, foremen, or mechanics. The same practice is still to be found in many small establishments today.

Just as there were outstanding and capable industrial managers many years ago, so were there many able tooling protagonists, some of whom were outstanding inventors and even mechanical geniuses. To some of these we are indebted for the concepts of the principles upon which modern tool engineering is based. For the most part they were, and their counterparts of today are, practical men possessed of a broad empirical knowledge acquired from long experience with manufacturing trials and practices. Tool engineering strives for the means to circumvent the many years of haphazard experience and breach the limitations imposed by restricted empirical knowledge.

Toward the end of the last century there began to develop a new idea of industrial management and organization. A vast general increase in the application of the natural sciences to engineering, medicine, agriculture, and other areas of activity pointed the way to a similar trend in industry. A continuing enlargement of the size of industrial enterprises brought forth more complex and extensive problems and, at the same time, presented opportunities for a more specialized and concentrated study of them. The entrance into the manufacturing field of many technically trained engineers brought the influence and viewpoint of the mathematician, chemist, and physicist. So long as the products of industry were simple devices that could be fabricated entirely by the ordinary high-grade mechanic, the aid of the engineer was unnecessary; but as the design and also the manufacture of many products became more complicated and abstruse, the engineer found his way into the area of industry.

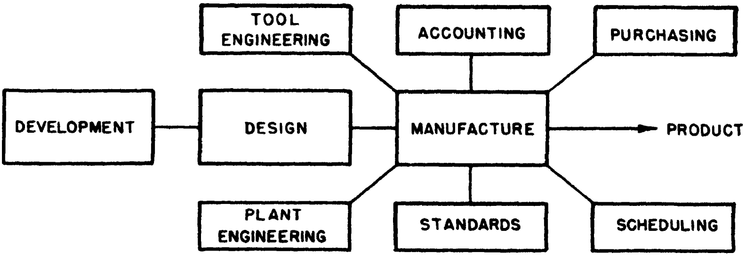


Fig. 1. The function of tool engineering as a manufacturing service.

Among the concepts introduced by the new order was one that all those engaged directly in production should be relieved of all planning, preparation, and calculations and that those functions should be assigned to specialists capable of applying to them the utmost warranted skill and knowledge. A diagram of the scheme for carrying this out is shown in Fig. 1. The steps of development and design bring a product to where it can be manufactured. The actual manufacturing effort is served by specialists who provide technical aids and physical equipment for efficient performance. Tool engineering is one of them.

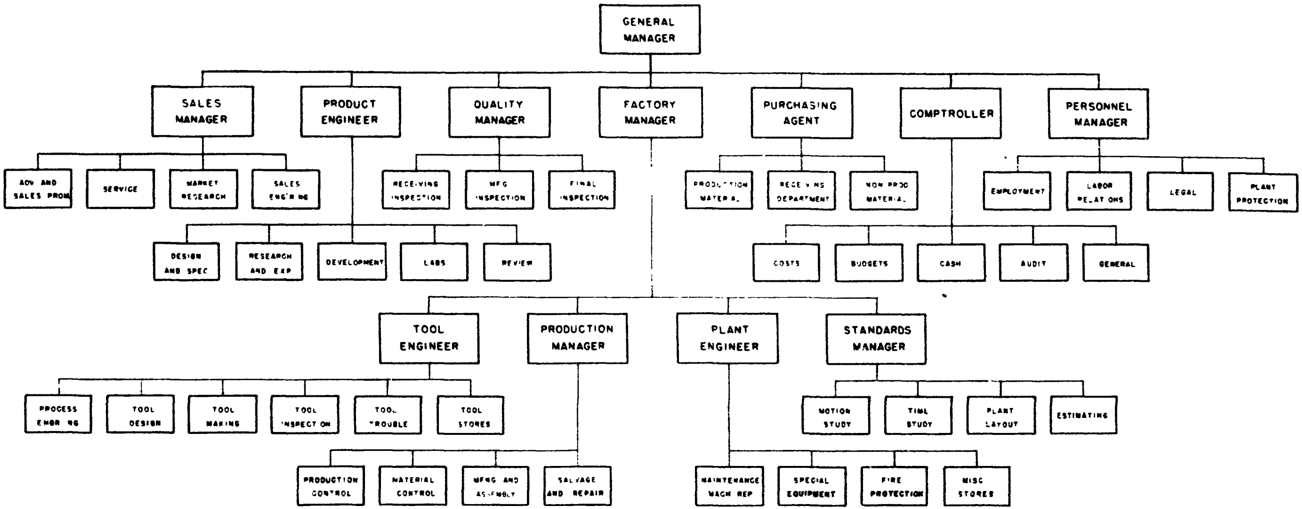


Fig. 2. A typical industrial organization chart.

The place of tool engineering in an organization

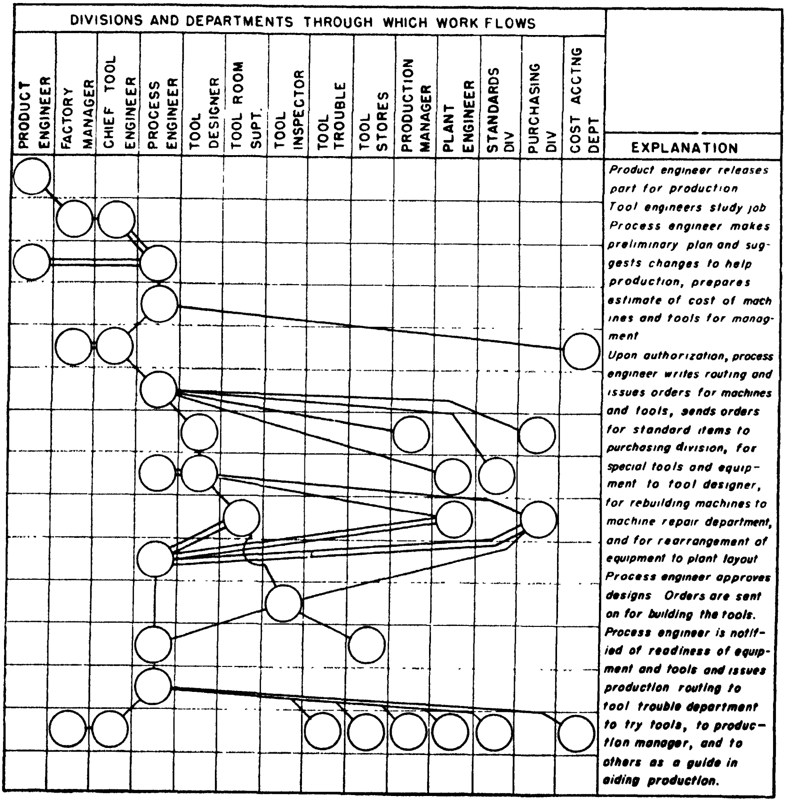
The chart of Fig. 2 represents a typical industrial organization. There are as many variations in organization as there are establishments, but they all possess the same characteristic, a team of specialists working together for a common end. This particular arrangement is not offered as an ideal pattern, but merely to illustrate the relative position of the tool engineer and assist in a detailed study of his responsibilities and activities. As one of the members of the staff of the manager responsible for factory operations, the tool engineer is in a position to plan and control the diligent dispatch of his duties and at the same time co-operate closely with the others (production manager, plant engineer, and standards manager) charged with production. Under the direction of the tool engineer are the departments (process engineering, tool designing, tool room, tool trouble, and tool stores) which represent the major subdivisions of his interests.

The title "tool engineer" has been applied to the head of the division in the sense that he symbolizes its character. In some plants he is known as the chief tool engineer; in others as the master mechanic, and sometimes as the production engineer or manufacturing engineer. In reality, all bona fide engineering employees specializing in any department of the tool engineering division can be termed tool engineers, although often they have titles designating their particular specialties; such as process engineer, tool designer, or tool room supervisor.

The duties of the tool engineer

The general responsibility of the tool engineer is to provide the industrial organization with the tools, machines, and information to make the products decided upon by the management. The chart of Fig. 3 depicts the way he goes about doing that. Any recitation of procedure must necessarily be hypothetical because differences in details will be found in every real setup. Reference should be made to each step of the chart of Fig. 3 as the steps are taken up in the following description of preparation for production.

The product-engineering division designs the article and sends a blueprint of the design drawing, together with a notice called an engineering release, to the manufacturing division. The chief tool engineer and the process engineer often discuss the job together if it promises difficulties. Several methods are usually feasible for making a part, and the process engineer must select the one which promises to provide the desired quality at the lowest cost. One choice may call for a large investment in special machinery but offer a low labor cost. On the other hand, another may require a smaller fixed expenditure, because of the use of standard equipment, but entail a higher labor charge. A third may represent a compromise. The final decision generally belongs to management, which is accountable for the financial policies, but the tool engineer must prepare the outlines of the proposed processes and preliminary comparative estimates covering the cost incumbent upon each. This informa-



Product engineer releases part for production

Tool engineers study job

Process engineer makes preliminary plan and suggests changes to help production, prepares estimate of cost of machines and tools for management

Upon authorization, process engineer writes routing and issues orders for machines and tools, sends orders for standard items to purchasing division, for special tools and equipment to tool designer, for rebuilding machines to machine repair department, and for rearrangement of equipment to plant layout

Process engineer approves designs Orders are sent on for building the tools.

Process engineer is notified of readiness of equipment and tools and issues production routing to tool trouble department to try tools, to production manager, and to others as a guide in aiding production.

Fig. 3. An outline of procedure of tooling a part for production.

tion may be submitted to the cost department of the accounting division for a check against past performance.

Throughout the tooling study the tool engineer may discover means of facilitating manufacture or reducing costs through changes in the design of the part. When such changes appear desirable, he suggests them to the product-engineering division and seeks to have them made. In this connection, good judgment and an understanding of the product designer's problems are necessary.

After the management has decided upon proceeding with the manufacture of the article upon the basis of the preliminary estimates, the process engineer prepares a detailed estimate of the cost of each item of machinery, tooling, and equipment required and requests authorization for the necessary expenditures. He writes the process or route sheet, which is the formal expression of the master plan for preparation and use of the tools, machinery, and equipment. Examples of these forms are given in Chap. 8. He issues orders and instructions for the purchase, design, construction, and disposition of all these items and sends these orders to those who must subsequently participate in the tooling program. Effective manufacturing depends upon adequate preparation. Production proceeds smoothly, and the final product is right only if the preparation is complete and each step is correct.

Copies of the process plans go to the production manager to apprise his division of the steps that are being taken and to serve as a basis for material and factory schedules. Likewise, copies sent to the standards division provide information for plant layout and job studies. The plant engineer receives the same information, so he can supply the production line with housing, material-handling facilities, air, electricity, water, and other services. Thus, those concerned with getting production under way and keeping it going are enabled to co-ordinate their contributions.

Acquisition of the machine tools and other equipment for the manufacture of the part may entail the selection and procurement of standard machines, the design and fabrication of special equipment, or alteration and adaptation of machinery on hand. One, two, or all of these measures may be necessary for any one case. Their successful conduct is essentially the responsibility of the tool engineer. Through specifications to the purchasing department he arranges for procurement of machines. Special machinery may be designed in the tool-engineering department or in collaboration with outside specialists who are, of course, themselves tool engineers. Instructions and designs for equipment alterations logically begin with the tool engineering division. They may be carried to completion by the same group, although in many cases that is done by the plant engineer's division using the same facilities as for plant maintenance.

In the tool-engineering division, jigs, fixtures, cutting tools, dies, gages, and attachments are designed in the tool design department in conformance to the process plans for production of parts of the required quality at the lowest possible cost and then built in the tool room. If the division is overloaded, some of this work may be let to outside contractors, who are, in effect, free lance tool engineers. It is not uncommon for changes in product design to come through after the tooling program has been far advanced. Ingenuity and resourcefulness must then be exercised to prevent unnecessary waste and complications.

In most cases, time is a factor in the tooling of a part, and the management requires a schedule from the tool engineer as to when it will be possible to start the various stages of production. In that event, it is necessary to schedule and follow each item while it is being designed and fabricated and to improvise means for overcoming unforeseen difficulties.

Finished tools are routed to the tool inspection department where they are checked. When passed, they are sent to tool storage and notice is forwarded to the process engineer. In this capacity, the tool engineer must be able to prove his plans and designs. If what has been done is sound, the problems encountered at this stage will not be difficult but sometimes are challenging. It is here that the tool engineer has a chance to display his ability for solving the problems assigned to him; both in the way in which his plans and tools perform under the acid test of production and in the ingenuity and analytical insight he is able to bring to bear upon perfecting their performance. He is expected to instruct the tool trouble men, production foremen, and set-up men so that maximum efficiency is assured.

Even with an article in production, the responsibility of the tool engineer is not altogether discharged. Whether production is maintained or increased, he is expected to be alert to observe and take advantage continually of improvements for better performance.

The two parts of tool engineering

As was stated in the definition of tool engineering and illustrated by the duties of the tool engineer, there are two inseparable major parts to this subject. They are planning and design. Production plans cannot be carried out without the creation of the jigs, fixtures, and so on, which they presuppose; but, likewise, efficient tools cannot be designed and built without a co-ordinating plan. In small plants the two functions, planning and designing, may be undertaken by one person and thus not be readily distinguishable. In large organizations one individual, called a process engineer, or group does the planning. Another designs the tools. Each, however, must have a clear understanding of the province of the other for proper co-ordination and efficient results. In the final analysis, each is a specialist in the field of tool engineering.

The analytical approach to tool engineering

The analytical approach to tool engineering goes beyond the entirely practical and empirical approach to the solution of problems by using more exact methods and an appreciation of principles.

The scientific ideal can be only partially realized by the tool engineer. Fundamental knowledge applicable to many of the processes of production is not complete. Where it leaves off, the engineer must go on with the help of judgment and experience.

For many problems an approximate solution by empirical means is expedient, and more precise results do not justify the added expense of a more rigorous inquiry. Even in such cases, the engineer will find his judgment abetted by an understanding of basic laws. On the other hand, there are always circumstances where the application of engineering principles is not only desirable but profitable. In such cases, the tool engineer must be prepared to offer means of securing refined results.

A summary of the general problems of process and tool engineering

The purpose of this text is to show how the major problems met by the tool engineer are attacked and solved. Therefore, a list of the chief problems of tool engineering will serve as an outline of what this book contains.

Tool engineering has two obligations. They are:

1. To devise means and equipment to achieve and maintain a required level of quality in a manufactured product.
2. To accomplish the required results in the most economical manner.

The second obligation always governs the first. Whenever a problem of methods or equipment is met, the question of economy will be found among the first to be answered. Consequently, as an aid in solving subsequent problems, the principles of economy, the solution of problems of economy, and the methods of realizing economy will be presented first.

As was implied in the outline of the duties of a tool engineer, before an appreciable expenditure for any project is justified, an estimate of its cost is good sense. Estimates serve to prove the economy of proposals. Thus, the principles and procedures of estimating will be the second general problem to be considered.

Ease of manufacture must always be considered in product development and design. Where the tool engineer is in a position to offer suggestions to improve design, it is his duty to do so. To this end, an understanding of the problems of the product designer is helpful. Therefore, some of the principles of product design and means of improvement from the standpoint of manufacture will be presented.

The process or tool engineer plans to bring men, materials, machines, and tools into operation. Groups of operations make up processes resulting in the desired ends of a manufacturing program. One of the vital problems of tool engineering is that of building up these combinations. In that endeavor a necessary prerequisite for success is a knowledge of common methods, techniques, machines, and tools. It is assumed that the student is equipped with that knowledge. The principles which point the way to effective utilization of it will be presented.

The design of efficient tools, like the design of other mechanisms, must be based upon basic laws. The use of such principles in tool design will be stressed in the treatment of that subject.

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2 PRINCIPLES OF ECONOMICS

The importance of economics to the tool engineer

Tool engineering is an adjunct of industrial enterprise that must earn profits to exist. The only source of profits is a favorable spread between the selling price and cost of the articles manufactured. The tool engineer's responsibility is to supply the equipment, machines, and tools for manufacturing at the lowest possible cost. But mere recognition of this situation is not enough; specific means must be adopted to insure the desired results. Just as the tool engineer is expected to apply science and technology to the solution of his problems, so he must also understand and conform to certain principles of economics and be able to utilize them with the same degree of reasonable accuracy as he does physical precepts.

For a solution of any basic problem in tool engineering, the answer must be found to three questions:

1. What is to be done?
2. By what methods and with what tools can it be done?
3. What is the best or most economical method?

For a logical analysis, the requirements of a situation must be defined. Generally, the tool engineer has at his disposal more than one method or process and several possible designs for the tools and equipment to do a job. The choice must be made of those factors which will give the required results at the lowest cost. Success in tool engineering depends in a large measure upon ability to ascertain costs and demonstrate the extent of the economies in any situation. For this, an understanding of the nature of cost is essential and is the purpose of this chapter.

One of the outstanding characteristics of the large industrial units of this country employing tool engineers is the great investment in physical equipment required to make them possible. It is not uncommon in automobile plants for the retooling costs of one model to amount to several million dollars. Money is as important for a tooling program as steel or machinery. If the tool engineer is to receive the respect that he deserves, he must be acquainted with the fundamentals of all the aspects of tooling. He must be able to "speak the language" of the business and financial men upon whom he is dependent for the capital requirements of his projects and prove to them his effectiveness in terms that they understand. The story has been told of the banker who was called upon for a loan for expansion by a company with likely prospects. He was impressed by the designs of the products and by the selling organization and agreed to the loan providing none of the money would be spent for frivolous developments such as jigs and fixtures. At that point there was need of a capable tool engineer, to demonstrate to the banker in terms with which he was familiar that—contrary to his beliefs—jigs, fixtures, and all tools properly applied could save his money and provide him a greater return.

This discussion is not intended to imply that the tool engineer should be an expert economist any more than he must be an authority on atomic energy or celestial mechanics to understand the physics that he uses. He should, however, possess an appreciation of the proper use and importance of the principles that will co-ordinate his activities with the economy in which he is a participant.

FUNDAMENTAL CONCEPTS OF ECONOMICS

Selections from simple alternatives

Occasionally, the solution of an economic problem involves only a choice of present or near future advantages. An example of this is the selection of the design of and method for making the welded beam illustrated in Fig. 4 in several forms. The beam on the right is a casting weighing 9¾ pounds; that in the center is a welded counterpart weighing 11 pounds; and the one on the left is a welded construction based on a functional analysis and weighing 7 pounds. The following tabulation shows the relative costs[1] of the three forms.

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[1] Cost data furnished by the Lincoln Electric Company, Cleveland, Ohio.

Item	Form		
	A	B	C
Casting (not including pattern)	$2.57	$ ...	$ ...
Steel	...	0.33	0.21
Cut and fit	...	0.70	0.20
Weld	...	0.60	0.30
Machine (est.)	1.00	...	...
Total cost	$3.57	$1.63	$0.71

Thus, it is possible to effect a saving of 80 per cent by making it in the manner illustrated on the left in Fig. 4 as compared with the casting. Problems of this type are referred to by economists as cases of *immediate* or *present* economy, entailing a choice of one of two or more factors for an immediate result. Unlike more complex problems, time here does not enter as an influence on the choice.

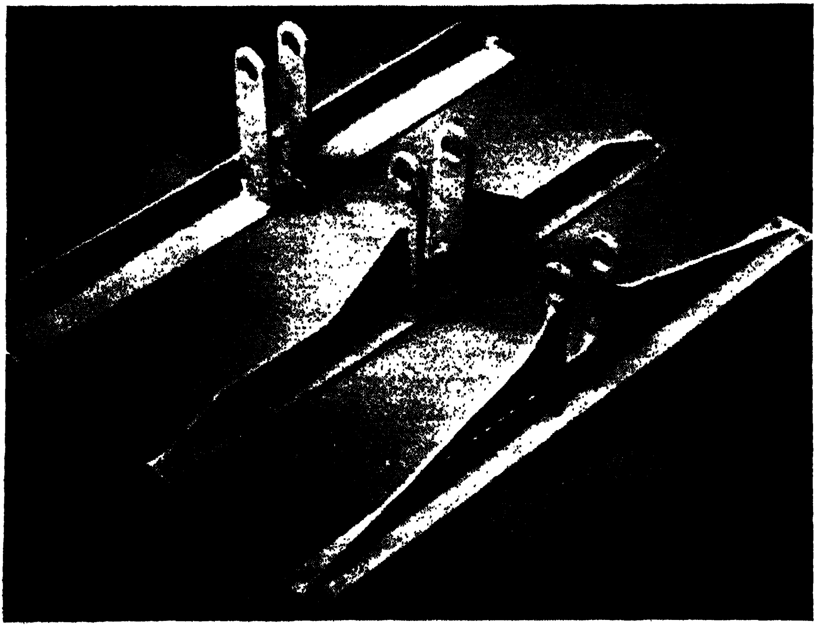

Fig. 4. Three forms of a beam to show differences in manufacturing costs. (Courtesy Lincoln Electric Co., Cleveland.)

Each of the choices produces a beam which for the desired purpose is identical with the others. There would obviously be no basis for comparison if one beam, even at a lower cost, did not meet functional requirements. Thus, in some cases, performance is the deciding factor and expense cannot be considered. For example, machine steel would not be considered in comparison with high-speed tool steel for a cutting tool because it costs less.

As a basis for a choice of identical results in immediate economy, either design, method, or material may present the alternatives. However evident the preference upon assembly of the facts, the task of compiling the necessary information and arranging it for a correct comparison may often require careful calculations and estimates.

In contrast to present economy are the more numerous cases in which investments are encountered which are affected by the passage of time. The dividing line between the two types is not always distinct. But although the details of approach may differ, the ultimate solution of economic problems in engineering generally requires an evaluation of the cost of two or more alternatives of obtaining equivalent results.

A special type of simple selection is that in which time of performance is the deciding factor. Every tool engineer is familiar with instances where extra expense has been incurred to secure or make a tool needed to consummate a program. In periods of shortages, it has not been unusual to resort to costly methods of securing results so that at least some advantage might be derived. Such cases are representative of abnormalities and should not be interpreted as refutations of economic principles.

Diminishing returns

A commonly observed condition in manufacturing operations, as well as in many other circumstances, is that a point is reached at which a maximum output per unit of input is secured and beyond which further intensification results in a decrease of benefits from a unit of input. This experience has been expressed in a basic economic principle called the *Law of Diminishing Returns*, which can be stated in the following manner: When there are a number of factors contributing to a system of production and one of these factors is limited or fixed, a point will be reached beyond which an increase in the variable factors will produce less than a proportionate increase in results. This statement has two specific implications:

1. At least one characteristic of the case is not changed.
2. All the other factors can be varied to improve results, but under conditions of increasing difficulty.

As an illustration of this law, consider a hypothetical operation for machining the face (containing the key) of the piece shown in Fig. 5 on a standard production milling machine. For a minimum equipment investment of $4500, including the milling machine, arbor, set of high-speed steel cutters, and one standard vise with a special set of jaws, we can expect the following performance:

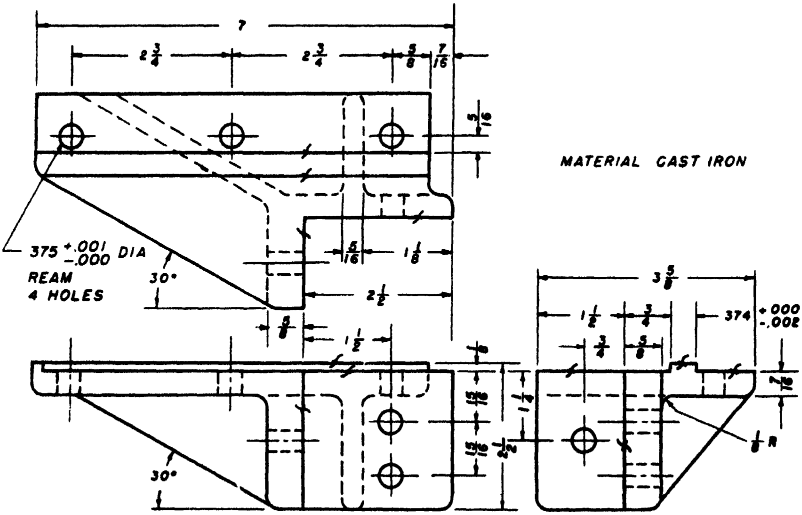

Fig. 5. A bracket. (Adapted from Paull and Sgro, *Applied Mechanical Drawing*, p. 60, Van Nostrand, 1936.)

Element	*Minutes*
Get part	0.10
Load and clamp in vise	0.20
Advance work to cutter	0.05
Mill surface	2.00
Return to starting position	0.05
Unload vise	0.05
Dispose of part	0.05
	2.50

This operation time of 2.50 min resulting from a direct investment in equipment of $4500 is represented by point *A* of Fig. 6. Now to improve the performance, suppose we invest an additional $50 to replace the high-speed steel cutters with ones having teeth of cemented carbide. We find that the cutting time is reduced to 0.60 min. The other elements are unchanged, and the time for milling each piece is down to 1.10 min, point *B* in Fig. 6. We are assuming that the machine has the capacity to take on the added load.

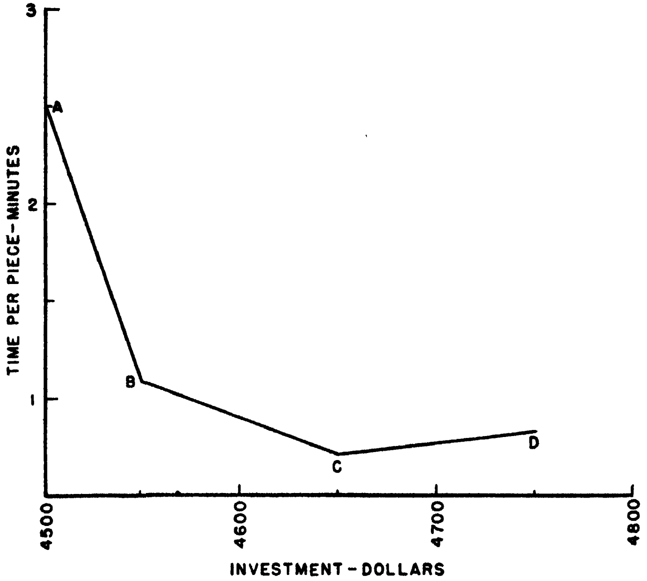

Fig. 6. Change in production rate resulting from increasing investment in the operation of milling the long face of the casting shown in Fig. 5.

The time for loading and unloading the vise of 0.40 min is less than the cutting time of 0.60 min, and we can add another vise with special jaws, this time to the other end of the table, at an additional cost of $100. The operator can be unloading and loading at one station while a piece is being cut. The time for producing one piece is now reduced to the time that the table is in motion, or 0.70 min, designated by point *C*. Incidentally, a comparable setup on a milling machine (employing a fixture at each end of the table) is shown for another part in Fig. 46.

So far, each addition to the operation has resulted in a decreasing return. We might arrange the vise jaws to hold two pieces or provide special fixtures for that purpose, at say an additional outlay of $100. Another set of cutters would be required if two pieces were to be milled at once, at say $150 per set. With that arrangement, the loading and unloading time is longer than the cutting time. We can reduce the time per piece somewhat, but certainly cannot cut it in half by milling two pieces at a time. Any further change that can be made appears to offer less than a proportionate decrease in the time per piece.

The point *C* of Fig. 6 is very near, if not actually, the point where further refinements in the milling operation are going to result in a larger cost for each piece produced—that is, the point of diminishing returns. It cannot be avoided as long as we hold to our original premise of doing the job on a standard milling machine. By resorting to an entirely different process, we could probably reduce the machining time and the unit cost. But that would constitute a departure from the law of diminishing returns, which requires at least one static condition to define the limits of the discussion. If all the original assumptions are abandoned, the results governed by them cannot then be expected to continue. As an analogy, we would not design a machine tool for use with high-speed steel cutters and then expect optimum results from cemented carbide cutters.

If the cutters in the milling example have been running at their most economical rate, an increase in speed or feed will decrease cutter life. More time will be spent in resharpening and resetting the cutters, to make up for the cutting time saved. The cost of cutter replacement can be expected to increase. It is likely that sufficient increases in speeds and feeds will materially increase both the time spent for the operation and the cost of equipment, as indicated by point *D* of Fig. 6.

The speed, feed, and power applied to a cutting tool are economically defined by conditions of diminishing returns. As a cutter runs faster and takes heavier cuts, with the consumption of more power, more metal is removed. However, a state is reached beyond which the cost of replacing and/or reconditioning the tool more than offsets the added production. At that point, diminishing returns have set in, and beyond that point it is not economical to operate the cutter.

Many examples of the influence of and limitations imposed by the law of diminishing returns are found in tool engineering. It is the point of diminishing returns that the engineer seeks in determining the maximum economical output that can be expected from a piece of equipment.

The extent to which the principle of transfer of skill is utilized in tooling is limited likewise by diminishing returns. As more and more skill is built into a tool or machine, it becomes more and more complicated and cumbersome, requiring greater attention and maintenance. Each part that becomes incapacitated from breakdown ties up others. The more components, the more frequently all are likely to be inoperative. Thus, although ingenious automatic machinery has been constructed and is used to make the parts of an automobile, none has been offered to fabricate the automobile completely and automatically; nor even the whole engine.

THE SOURCES OF COST

The cost of production

Most manufacturing operations are dependent upon investments which must be liquidated from the proceeds of their exploitation. The investment charges, together with service charges for a definite period of time, usually a year, are divided among the parts produced in that period. Thus, the more parts made, the lower the allocated charge against each one. In addition to the fixed and indirect charges, each piece manufactured requires a direct expenditure of labor, power, etc. The chart of Fig. 7 shows the relationship between the unit cost of an article and the number of pieces produced. The curve *ABC* represents the unit cost as determined by the number of parts produced within the period of time for which the charges against the operation accumulate. The line *ADEBF* represents the marginal or direct cost of each additional piece. It is practically constant after the first piece to the point *E*, for the production of a quantity of *E′* parts, where the law of diminishing returns begins to take effect. At a point *B*, the last of a total of *B′* parts has a marginal cost equal to the average cost of all the parts. After that the cost of making each additional part is greater than the average cost. It is evidently not economical to attempt production of more than *B′* parts under the initial conditions.

Notice that the chart of Fig. 7 does not show a historical sequence, but that the ordinate of each point stands for the results that can be expected from the operation if it is utilized for the production of the number of parts specified by its abscissa. The point *B* represents the unit cost resulting from complete economic utilization of the operation. At any other point there is a condition of either a decreasing or increasing cost potential. What the actual production and consequent unit cost are in any particular instance depends upon the demand for the output and not primarily upon the characteristics of the operation. Consequently, the method and equipment for performing the operation are normally selected to suit the sales requirements.

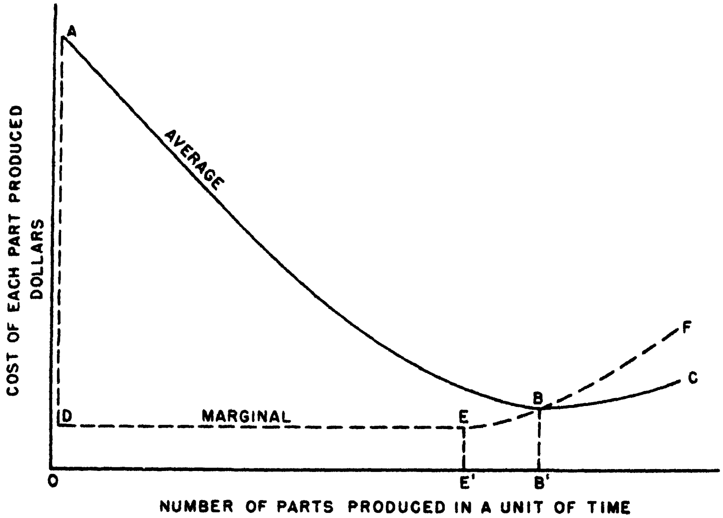

Fig. 7. The cost trend of a typical operation.

In accordance with the foregoing observations, the costs of production can be classified and described as:

1. *Fixed costs*, which are charges arising from the investment for a particular purpose and cannot be recovered except from payment for the services performed by the equipment. They are in their entirety independent of the amount of production and are assessed on the basis of the original commitment. They include depreciation, interest, taxes, and insurance.

2. *Indirect or overhead costs,* which arise from auxiliary functions or services contributing to efficient performance of the operation and its equipment and having no proportional relationship to the amount of output. In this class are management, office, engineering expenses, plant costs, and indirect labor.

3. *Direct costs* or operating expenses, which can be specifically charged to the output and vary in proportion to the quantity produced. They include direct labor, power, materials, and preparation costs.

This breakdown of cost is different from that normally used in cost-accounting work, but is presented here because it conforms to the way of looking at cost found in machine, tool, and equipment studies.

Fixed costs—the results of capital outlay

When an investment is made in machines, tools, or other equipment, an obligation is incurred against part of the earnings of the equipment to pay off and protect the original capital outlay. It is important to ascertain, therefore, just what constitutes the investment. For a piece of equipment it usually includes the catalogue

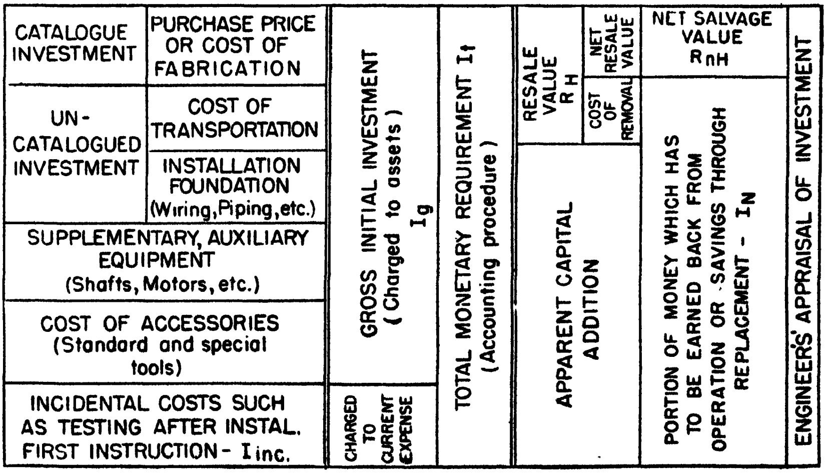
CATALOGUE INVESTMENT
PURCHASE PRICE OR COST OF FABRICATION
UN-CATALOGUED INVESTMENT
COST OF TRANSPORTATION
INSTALLATION FOUNDATION (Wiring, Piping, etc.)
SUPPLEMENTARY, AUXILIARY EQUIPMENT (Shafts, Motors, etc.)
COST OF ACCESSORIES (Standard and special tools)
INCIDENTAL COSTS SUCH AS TESTING AFTER INSTAL. FIRST INSTRUCTION - I inc.
GROSS INITIAL INVESTMENT (Charged to assets) Ig
CHARGED TO CURRENT EXPENSE
TOTAL MONETARY REQUIREMENT It (Accounting procedure)
RESALE VALUE RH
NET RESALE VALUE
COST OF REMOVAL
APPARENT CAPITAL ADDITION
NET SALVAGE VALUE RnH
PORTION OF MONEY WHICH HAS TO BE EARNED BACK FROM OPERATION OR SAVINGS THROUGH REPLACEMENT - IN
ENGINEERS' APPRAISAL OF INVESTMENT

Fig. 8. Elements of prime investment. (Adapted from Vorlander and Raymond, "Economic Life of Equipment," *Trans. ASME,* RP-54-2, 1932.)

price or cost of fabrication and also such necessary expenditures as transportation, accessories, and installation, as shown in the chart of Fig. 8. If I_t represents the total investment and I_g the gross initial investment, including catalogue or fabrication cost, transportation, and all auxiliaries and accessories,

I_{inc} = set up, try out, and testing costs,

$$I_t = I_g + I_{\text{inc}} \tag{1}$$

Accounting practice usually charges off I_{inc} to current expenses, but it is a justifiable part of the original total investment as a basis for determining the true cost of production.

In the event that new equipment replaces an older installation having a realizable value (R_{nH}) after removal costs, it is reasonable that that amount be subtracted from the total investment (I_t) in the new equipment to arrive at the net investment (I_N) for which fixed charges for the equipment should be computed. Thus:

$$I_N = I_t - R_{nH} \tag{2}$$

The value of old equipment

It is not uncommon for the equipment that is being replaced to have a book value greater than its true value. Its sale thus results in an apparent capital loss. Accounting practice favors charging this to the current profit and loss account on the proposition that past errors of judgment in evaluation on being realized should not be carried as a continuing burden against future earnings. The difference between book value and realizable value represents an amount that should have been paid out of past earnings. Some engineers follow the same reasoning in not including the apparent book loss as an investment consideration. Others contend that, in scrutinizing the economic possibilities of an investment, the capital loss should logically be considered as part of the obligation incurred by the new equipment in taking over the functions of the old. Whichever view is accepted, it would seem logical to be consistent in treating both the old and new equipment in the same manner for a comparison. If the old equipment is considered to be worth its realizable value only, then the proposed replacement should not be called upon to assume the added burden of the capital loss. But if the old is to be expected to continue discharging its obligation to its rated residual investment, including the apparent loss, then the new should be charged with making up the loss which its installation would bring about.

It is also not unusual for the cost of removing old equipment to exceed its true value. Thus if:

V_B = book value of old equipment,
R_H = sale value of old equipment,
R_C = cost of removal of old equipment,
K = loss from old equipment if replaced,

$$K = V_B + R_C - R_H \tag{3}$$

Under the circumstances where the displacement of the old equipment represents a net loss and the analyst considers that this loss should be assumed by the new equipment, the net investment may be written as:

$$I_N = I_t + K \tag{4}$$

The distribution of fixed costs

After the amount of an investment has been determined, the next step is to ascertain how much of it is to be charged against the production during any period of time. Actual impairment of the investment must be met by an equivalent charge for depreciation. Protection for the investment must be maintained through payments for taxes and insurance. These are the factors which will now be considered.

Depreciation

Most physical items experience a shrinkage in value with the passing of time, although the actual loss may or may not result from age. It is characteristic of mechanical equipment to suffer from use an impairment of its strength, accuracy, or efficiency. In that respect, the equipment can be thought of as imparting some of its original value to each unit that it works upon. On the other hand, equipment may deteriorate from causes that have no relation to the amount of use to which it is put. An idle machine will lose some of its substance from the action of rust and rot. Impairment from use and deterioration are aspects of *physical depreciation*, which is nearly always a function of time. The value of equipment may shrink also from *functional depreciation*, which is largely independent of time. It is encountered in the case of comparatively new equipment which has ceased to be economical because other designs have appeared which perform the same function better. It is found in the case of special equipment for a product which is no longer in demand because of style changes or market saturation. It is commonly referred to as obsolescence, illustrated by the replacement of belt-driven machine tools by those with individual drives in modern plants. Of the two types, functional depreciation is much more difficult to forecast; yet it is very real and important. In many instances it is the larger part of the total depreciation.

Allocation of depreciation necessitates the distribution of the investment in some manner over the life period of the equipment. Just what is the life of any particular production unit is often a problem in itself. A number of interpretations have been presented, and the more important will be discussed later. In most cases the length of life is not calculable because of the manifestly unpredictable factors of obsolescence. No one knows what the life of a machine will be until its end is reached. Consequently, resort is usually made to past experience as a basis for an enlightened guess. Permissible depreciation for tax purposes may also have to be considered. The length of life may vary from ten years or more for general-purpose machine tools not dependent upon the fortunes of any one product to a year or less for specialized jigs and fixtures for products subjected to frequent model or style changes.

Ways of distributing depreciation

Depreciation can be distributed over the lifetime of a piece of equipment by a number of methods. The most widely favored because of its simplicity and adaptability is the straight-line method which assumes that the decrease in value during the life term is directly proportional to the time elapsed. Thus, if:

I_N = original investment in dollars,
L = useful life of the equipment in years,
I_A = the value of the equipment at the end of A years in dollars,
d = annual cost of depreciation in dollars,
R_L = salvage value at the end of the useful life in dollars,
D_A = accrued depreciation to A years in dollars,
D = $1/L$ depreciation rate (percentage),

$$d = \frac{(I_N - R_L)}{L} = (I_N - R_L)D, \tag{5}$$

$$D_A = \frac{A(I_N - R_L)}{L} \tag{6}$$

$$I_A = I_N - \frac{A(I_N - R_L)}{L} \tag{7}$$

For simplicity combined with sufficient accuracy for many cases, the salvage value R_L may be neglected, since it usually is small, and

$$d = \frac{I_N}{L} = I_N D \tag{8}$$

Very few articles depreciate actually in direct proportion to time and the straight-line formula is only an approximation. It also does not take interest into account. However, the errors resulting from these shortcomings are usually of no greater order of magnitude than the inaccuracies inherent in any attempt to forecast future value, contingent upon so many possibilities. Hence, in most cases, the obvious simplicity of the straight-line method offsets its deficiencies. If during the life of the equipment, conditions develop to revise the original expectation, the allowance for depreciation can be adjusted most easily if the straight-line method is used.

Of the many other methods of spreading depreciation over the life of property, only a few have more than limited applicability, and only a brief reference to those is necessary. Three methods are based on the theory that interest earnings should be credited to the depreciation, reducing its charge to a certain extent. By the *annuity method,* interest on the remaining value of the asset each year is added to the allowance for depreciation to provide equal annual amounts to pay off the investment. By the *compound-interest method,* the interest on the amount that has been paid off is added each year to the periodic installment. For the *sinking-fund method,* a fund is actually, or assumed to be, created to which installments of equal amount are added each year and which is credited with annual interest earnings. None of these methods provides refinements in most cases warranting their complexity.

Another group of methods attempts to charge off heavier annual amounts for depreciation during the early years of life. This is in accordance with the actual depreciation trend of many articles.

By one of these, the *reduced-balance method*, a constant percentage is deducted each year from the value remaining from the previous period so that the item is reduced to its salvage value at the end of its life. It should be remembered that any such declining rate is based upon past experience, of which there is no guarantee of conformity in the future.

Efforts have been made by other methods to correlate depreciation charges with the rate of business activity; to charge off more when earnings are high and less during a period of depression. Thus, depreciation may be apportioned on the basis of operating time, production output, or sales volume. Such trends are difficult to forecast and add uncertainty to any estimate. They do have merit from an accounting standpoint in recording events after they have taken place, but obviously would add little to an engineering analysis that would be dependable.

Interest

When money is lent or invested, a return over and above the principal is expected for its use and the risks taken. This is interest, usually expressed as a rate in terms of a percentage of the principal amount for a definite period of time. Interest must not be confused with profit. Economists define interest as a rental paid for the use of borrowed capital which is presumed to be repaid; profit, a return beyond the original investment in an enterprise from which there is no specific guarantee of recovery.

An analysis of an investment in tools, machinery, or equipment is made to determine whether the capital is likely to be returned and all charges paid. It is logical to expect that earnings will cover an interest charge. Just what the rate should be is a question. Some think that it should be that of the market in which the money might be borrowed for the investment as, indeed, it often is. Others look at it somewhat differently: that the interest rate should be that which could be obtained if the money were invested elsewhere instead of in the equipment. Generally, the return that is expected varies with the risks. The more speculative the venture, the higher the calculated return in order to attract the capital. An investment in equipment is subject to a number of obvious risks. Some equipment, such as specialized machinery, is exposed to greater capital risks than other types. Risk likewise varies with the kind of business. Consequently, it has been suggested that a rate of return upon a capital investment should be selected to make the investment attractive in view of its inherent risks.

If equipment is depreciated, the interest charged each year should be upon the undepreciated balance. The interest is assessed at the end of the year, but the balance of the investment on which it is calculated is that which stood at the beginning of the same year. Thus, if depreciation is by the straight-line formula and:

I = the original investment in dollars,
L = the anticipated total life of the equipment in years,
r = the annual interest rate in per cent,

we have

$I \times r$ = the annual interest payment on the total investment which will be paid at the end of the first year,
I/L = the amount paid off to depreciation each year,
$\frac{I \times r}{L}$ = the interest payment at the end of the last year of the life of the equipment.

The average interest payment over the life span is

$$\frac{Ir + rI/L}{2} = \frac{Ir}{2}\left(1 + \frac{I}{L}\right) = \frac{Ir}{2}\left(\frac{L+1}{L}\right)$$

and the average interest rate is

$$R_A = \frac{r}{2}\left(\frac{L+1}{L}\right) \tag{9}$$

Taxes and insurance

Taxes and insurance likewise are proportional to the value of property. On the same basis as interest, if:

B = annual percentage for taxes and insurance,
B_A = average annual percentage allowance for taxes and insurance,

$$B_A = \frac{B}{2}\left(\frac{L+1}{L}\right) \tag{10}$$

The use of average rates

The average rates, R_A and B_A, are commonly accepted as approximations for any year in analyzing fixed charges. If the life is 1 year; R_A equals r; if the life is 2 years, R_A equals $\frac{3}{4}r$; and R_A approaches $r/2$ as the life becomes longer. The same applies to the relationship between B_A and B.

The nature of indirect costs

It often is not practical to attempt a minute determination of certain labor and materials costs. For example, although it is possible to weigh the amount of grease used on a particular machine, it is usually applied from a common container from which many machines are serviced, and it is not considered worth-while to take the pains to determine the amount of an individual application. Likewise, it is not generally considered practical to try to apply to each operation the time spent in moving parts to and from its station. Such supplies and effort are classed as indirect material and indirect labor. Other contributions to the efficient performance of an operation which are difficult of direct allocation are building maintenance (real estate taxes, insurance, and depreciation), light, heat, ventilation, supervision, office, clerical, and engineering expense. Some of these services may not even make direct contact with the particular operation, but all are necessary to its continued performance; otherwise, they would not exist in an efficiently managed enterprise. They are grouped together as indirect costs or overhead and charged by various methods to the productive departments and, ultimately, to each specific operation and its equipment.

Ways of distributing indirect costs

All overhead components do not contribute to each operation in the same proportion nor to all operations equally. The problem, therefore, is to find some means of equitably distributing the indirect charges in proportion to the actual benefit derived from them in each stage of manufacture. Any solution is necessarily arbitrary to some extent. The results obtained by one method are useful under certain conditions, but misleading for others, where another method may be found desirable.

Many methods have been developed for distributing overhead as well as other charges. Some are not often employed, being useful only for the refinements that they provide cost accounting under unusual circumstances. Others are widely adaptable to accounting methods of determining current costs and to engineering studies, comparisons, and estimates. The more important methods that will be discussed are:

1. Direct material.
2. Unit of production.
3. Direct labor dollar.
4. Direct labor hour.
5. Machine hour rate.
6. Space rate.

More than one of these methods are frequently employed at one time, inasmuch as each is peculiarly fitted for prorating certain types of costs. To do so, however, adds complexity to the analysis, and judgment must be exercised in the choice of methods to strike a balance between refinement of procedure and practical simplicity.

Distribution of indirect costs by direct material method

Overhead expense may be distributed on the theory that it is incurred in proportion to the value of the direct materials consumed. This method is simple but does not allow for the usual situation wherein some of the material is fabricated without the use of much equipment, whereas other material in the same plant requires expensive machinery requiring considerably more labor, power, maintenance, and floor space. However, for the allocation of material expenses such as purchasing, storage, and handling, the method is useful.

By this method:

$$R_m = \frac{O}{C_m} \tag{11}$$

where

R_m = overhead rate in dollars for each dollar of direct material cost,
O = overhead expenses in dollars,
C_m = direct material cost in dollars.

Unit of production method

By this method the overhead expenses are divided equally among all the parts produced. For one product mass-produced or a few products of close similarity, this procedure can be recommended and by it:

$$R_u = \frac{O}{N} \tag{12}$$

where

R_u = overhead rate in dollars for each unit produced.
O = overhead expense in dollars.
N = number of units produced in period during which overhead costs are incurred.

Direct labor dollar method

The assumption of this method is that overhead expenses are in proportion to the direct labor cost. This method is simple and provides accurate results where labor is the main productive element and wage rates are fairly uniform. On the other hand, it may not be an accurate indicator where machines of greatly different capacity and size are operated. If applied to such overhead items as arise more or less from the amount of direct labor, like supervision and personnel department costs, it can provide a reliable distribution. On the basis of this method:

$$R_{LD} = \frac{O}{C_D} \tag{13}$$

where

R_{LD} = overhead rate in dollars for each dollar expended for direct labor (direct labor dollar overhead rate),
O = overhead expense in dollars,
C_D = cost of direct labor in dollars.

Direct labor hour method

For this method, it is assumed that overhead expenses are proportional to the number of man-hours directly consumed. It is obviously akin to the labor dollar method and has most of its advantages and disadvantages. By this method:

$$R_{LH} = \frac{O}{H} \tag{14}$$

where

R_{LH} = overhead rate in dollars for each hour of direct labor (direct labor hour overhead rate),
O = overhead in dollars,
H = hours of direct labor.

Machine hour rate method

This method is based on the assumption that overhead costs are incurred in direct proportion to the number of hours the machinery is operated. It is well suited to estimating the cost of production on a single machine, even where a number of articles are processed at different times on the same machine. It does not take into account the relationship between machine time and man time, which obviously is not constant for different installations.

This is really a combination method of allocating costs and its procedure is somewhat more complicated. Three steps are usually taken in arriving at the machine hour rate.

1. The overhead expenses are distributed to the productive departments of the plant on the basis of the benefits each department is estimated to have received.
2. In each department the expenses are redistributed to the individual machines on an estimated basis of their applicability. Some expenses may be prorated in accordance with the direct man-hours devoted to the machine, others in accordance with the space occupied, and so on.
3. All the charges applied to a particular machine are combined and divided by the total number of hours of operation to give the machine hour rate.

Thus:

$$R_B = \frac{O_m}{H_m} \tag{15}$$

where

R_B = burden rate or machine hour rate in dollars per hour,
O_m = charges applied to the machine over a definite period of time, in dollars,
H_m = number of hours of operation of the machine during the same period.

Space rate method

The amount of space occupied by a machine has an evident relationship to certain overhead expenses. Typical of these are building expense, heat, light, ventilation, and service equipment, such as cranes and conveyers.

Space charges should be based on more than the actual area underneath a machine. If

A_t = total area of the production department in square feet,
A_m = total area in square feet in the department occupied by machinery, including that assigned to auxiliary equipment, operators, and material in process,

A_w = all area for aisles and general purposes in square feet,
A_u = unoccupied space in square feet,

then

$$A_t = A_m + A_w + A_u \tag{16}$$

and if

a_m = area in square feet occupied by the particular machine plus auxiliary area assigned to it,
a_w = share of area in square feet of aisles, etc., to be carried by the machine,
a_t = total area in square feet assigned to the machine,

so that

$$a_t = a_m + a_w \tag{17}$$

then

$$\frac{a_m}{a_w} = \frac{A_m}{A_w} \tag{18}$$

and the total area with which the machine should be charged is:

$$\begin{aligned} a_c &= a_t + A_u \frac{a_t}{A_m + A_w} \\ &= a_m\left(1 + \frac{A_w}{A_m}\right)\left(1 + \frac{A_u}{A_m + A_w}\right) \end{aligned} \tag{19}$$

The more efficiently space is utilized so that A_u approaches zero, the more nearly a_c is equal to $a_m\left(1 + \frac{A_w}{A_m}\right)$. If

O_D = total overhead assigned to the department for space charges in dollars,
R_D = department space rate in dollars per square foot,

$$R_D = \frac{O_D}{A_t} \tag{20}$$

and the space charge to the individual machine for the defined period of time is

$$C_s = R_D a_c \tag{20a}$$

Maintenance

Equipment requires upkeep if it is to continue functioning efficiently. Maintenance has considerable effect upon physical depreciation, but little upon functional depreciation. Much of the wear and tear can be obviated by good care, and replacements can restore worn units to practically new condition. Whether maintenance can do anything to retard obsolescence is doubtful. Of course, a machine can be redesigned and rebuilt to compete more efficiently with later models, but that is a matter of improvement that should not be confused with maintenance.

In accounting practice, maintenance is usually considered a part of, and charged to, overhead. It often is not worth-while to segregate it as a separate item. On the other hand, maintenance costs can be closely identified with a specific unit of equipment and they provide a valuable part of the record of its performance. For such cases it may be treated separately from other overhead items. Data on maintenance costs for equipment in a plant are a matter of record, and such information for projected installations must be obtained from the past records of similar types and, of course, can only be estimated.

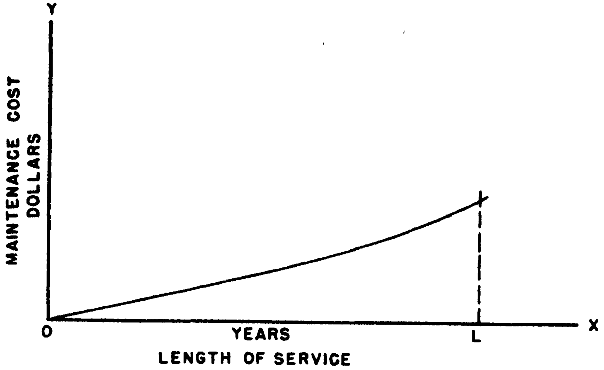

Fig. 9. General relationship between equipment use and maintenance costs.

Maintenance appears in three forms: There is the daily attention of lubrication and adjustment which increases with the rate of production. Also, a certain upkeep is necessary regardless of use, such as the replacement of parts which deteriorate with age, which is a function of time. And then there are repairs which have a complex dependence upon service and time. In general, maintenance costs increase as some function of time, as indicated by Fig. 9, with a constant production rate. For normal periods of equipment life, the cost-of-maintenance curvè, in most cases, can be closely approximated by a straight-line relationship shown in Fig. 10.

Within a definite period of time, say a year, maintenance costs can be expected to show an increase with increased production; an expression for the annual cost of maintenance of equipment in relation to various rates of production might be written as:

$$M_y = m_1 + m_2 f(N) + m_3 f(H) \tag{21}$$

where

M_y = annual cost of maintenance,
$f(N)$ = a function of the number of parts produced during the year,
$f(H)$ = a function of the age of the equipment, m_1, m_2, and m_3 being constants.

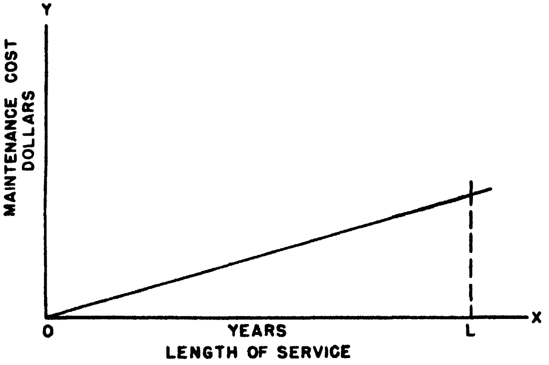

Fig. 10. Maintenance cost on straight-line basis.

Direct costs

As has been demonstrated, some of the costs of production are unescapable consequences of the investment and must be met regardless of the output. Others have a closer connection to the use of the equipment and vary more or less with its activity. Of these the direct costs or operating expenses are directly proportional to the output. They include applied labor, power, lubrication, preparation, setup, and material. Their magnitude for an undertaking can be estimated closely from past performance of similar jobs.

How cost figures are obtained

Information for determining direct or indirect costs is usually obtainable from the records of the organization in which it is used.

Adequate control of an industrial organization requires that all expenditures be accurately recorded. Not only are accounts kept of the purchases of supplies and materials, but when these items are drawn from stores for processing or service, proper vouchers must be made up and posted to attest to the distribution. Labor applied to any definable task is recorded on time and job cards, which serve as a basis for payment. General expenses likewise are recorded. The information is systematically gathered, and entered and totaled under appropriate headings by the cost accounting department which also seeks to apportion all charges to the individual operations and products equitably. From this source the tool engineer can secure much of the basic data for his studies, although he may have to supplement it with estimates to suit his purposes.

Summation of production costs

We are now in a position to set up expressions for annual and unit production costs. For the fixed charges:

$$C_F = I_N(D + R_A + B_A) \tag{22}$$

where

C_F = total annual fixed charges in dollars,
I_N = net investment in equipment in dollars,
D = $1/L$ = annual percentage allowance for depreciation and obsolescence,
R_A = average percentage rate for interest,
B_A = average percentage rate for insurance and taxes.

The general expression for overhead allocation can be written:

$$O_i = R_iC_i \tag{23}$$

where the subscript i is the general indicator, for which, as the case may be, we can substitute m for direct material method, L for direct labor method, etc. Thus,

O_i = partial overhead charges in dollars per year; such as O_m for overhead charges for items figured by direct material method; O_L from items by direct labor method, O_s from items by space rate method, and so on.
R_i = rate for overhead distribution method corresponding to O_i; such as R_m for rate by direct material method, R_L for rate by direct labor method, R_s from items by space rate method.

C_i = number of units of determining factor, such as C_m dollars per year of material for direct material method, C_D dollars per year of direct labor, a_c square feet of space for space rate method, etc.

The total annual charges against an operation or against the equipment used exclusively for it are:

$$C_A = C_F + M_y + C_D + O_D + C_m + \Sigma O_i \tag{24}$$

where

C_A = total annual cost of operation in dollars,
C_F = annual fixed charges in dollars,
M_y = annual maintenance cost in dollars,
C_D = annual cost of direct labor,
O_D = annual cost of other direct charges such as power, supplies, etc., in dollars,
C_m = annual cost of direct materials in dollars,
ΣO_i = sum of indirect cost in dollars,
$= O_M + O_L + O_s + \cdots$

If N parts are to be produced in the year, the unit cost is

$$C_P = \frac{C_A}{N} \tag{25}$$

This enumeration is more comprehensive than required for most analyses and estimates. For practical purposes it is found in modified forms. Ways by which it is adapted to specific problems will be discussed in the next chapter. However, it is generally conceded that formulas should not be used without an understanding of their basis and derivation, and the complete concept is necessary if the adaptations are to be understood and applied properly.

The curve of Eq. 25, expanded by means of Eqs. 22, 23, and 24, is of the type shown in Fig. 7. In that diagram, the marginal lines represent the direct unit costs,

$$\frac{C_D + O_D + C_m}{N}$$

which are practically constant until the point E is reached, when the effect of diminishing returns begins to be noticed. It is at point E that the direct costs and some of the indirect costs become complex functions of the output and are difficult to evaluate. However, any appraisal after that stage is really never necessary, as the problem then becomes one of finding a more prolific method of doing the work. It is sometimes important, though, that the engineer be able to recognize the saturation point.

SUMMARY

The basis of economics is that no benefit is derived without some cost. The tool engineer must show results at the lowest possible cost. To do this, he must know the nature of costs.

Sometimes selection of a desirable method may be made from *simple alternatives* merely by adding the expenses for each to find its total cost and choosing the one calling for the least immediate outlay. More often, though, costs are not so easily determined because they have a relationship to time.

A basic concept of economics is that of *diminishing returns*. It reflects common experience with situations reaching a point after which added effort or expenditure results in a less than equal increase in output. This is often found in tooling practices.

Costs appear in three forms. They are (1) *fixed costs*, resulting from capital investments; (2) *indirect costs*, arising from auxiliary service (both of the foregoing must be distributed fairly and taken into account for a reliable estimate of costs); (3) *direct costs*, which are readily ascertainable for a project.

QUESTIONS

1. Why is an understanding of pertinent economic principles important to the tool engineer?

2. What is meant by *selection from simple alternatives?* Is money cost always the only basis for simple selection?

3. What is meant by the *Law of Diminishing Returns?* How must it be qualified?

4. Show that a point of diminishing returns is reached in any metal cutting operation if the cutting speed, at first low, is raised enough.

5. What are the three forms of production costs?

6. What is the trend of cost as production from an operation increases? Assume that the operation requires a fixed investment in equipment.

7. What are fixed costs and from what are they derived?

8. What items may have to be included in an investment in equipment?

9. If a comparison is to be made between a new piece of equipment and an old piece of equipment it is to replace, how may the loss on the old equipment be taken if its book value is greater than its real value?

10. Describe the two types of depreciation.

11. What is the most widely favored way of distributing depreciation? How is it applied?

12. Describe several ideas underlying the distribution of depreciation by various methods.

13. How is average interest rate ascertained?

14. How is the average rate for taxes and insurance ascertained?

15. What are indirect costs? Give several examples.

16. Name six ways of allocating indirect costs.

17. Describe the following methods of distributing indirect costs and state advantages and disadvantages for each: (a) direct material method, (b) unit of production method, (c) direct labor dollar method, (d) direct labor hour method.

18. Describe the machine hour rate method of distributing overhead. For what purpose is it well suited?

19. Describe the space rate method of distributing overhead. To what indirect costs is it related?

20. What are the three forms of maintenance?

21. What relation does maintenance cost have to the rate of production?

22. How are cost figures obtained in a plant?

23. To what are the total annual fixed charges against a piece of equipment equal?

24. Of what do the total annual charges against an operation consist?

25. If N parts are to be produced by a piece of equipment in a year, what is the cost per piece?

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3 PROBLEMS OF ECONOMY

The kinds of economic problems found in tool engineering

In processing and tooling, a number of alternatives are offered to produce a desired result. The problem is to find the one which promises the lowest net cost. Typical problems of this sort are:

1. The comparison and selection of equipment on the basis of getting a desired result at the lowest cost.
2. The determination of the time during which savings from the use of certain equipment will pay off the investment; a decided factor in equipment life.
3. The comparison and selection of tooling and determination of its ability to pay its own way.
4. The lot sizes in which parts shall be manufactured and for which equipment and tooling shall be prepared.
5. The speeds at which cutting tools should be operated for lowest cost.

The factors that must be taken into account in solving problems of these kinds and ways of making meaningful comparisons will be taken up in this chapter.

COMPARISON AND SELECTION OF EQUIPMENT

Typical problems calling for comparisons

There are a number of situations for which the tool engineer has need for a basis of comparison of costs in order to select the method or equipment for doing a job most economically. Problems which are frequently met are typified by the following situations:

1. A comparison of two or more proposed installations or methods to do a job, usually for a new project.
2. A proposal for new equipment to replace that which is cur-

rently operating. The present installations may have become worn or appear obsolete; or production demands may have risen beyond its original intended capacity.

3. A survey to determine the desirable extent of combining operations. Some combinations are so natural that they are not questioned. If two parallel surfaces are to be milled, it is accepted practice to use straddle milling cutters. But for cases where the natural course is not apparent, comparison of the costs of each option must be made. Although there may not be justification for complete combination of all operations of a process, there may be economy in partial combination.

4. A decision on whether to invest in equipment to manufacture an article or purchase that article partly or wholly made.

Ways of deriving economic advantages

A choice of methods and tools is almost always offered for any particular job because of the varied possibilities of relegating human functions to machines and of combining mechanical activities. Time and effort required of a workman to perform a task may be reduced by several means, such as:

1. The transfer of skill, as illustrated by the common drill jig, which embodies the accuracy imparted by a skilled toolmaker in positioning the cutting tool so as to require less time and skill on the part of the operator in performing the drilling operation.
2. The transfer of thought or attention (illustrated by the automatic screw machine, for which constant observation and manipulation by the operator are not required to assure continuous performance).
3. The transfer of energy whereby effort expenditure by the operator is passed over to the machine (as by air- or hydraulic-clamping devices).
4. The addition of conveniences to the machine, like automatic gages for grinders.
5. The employment of means of duplication, like die casting.

Machine functions may be combined with such beneficial results as:

a. The elimination of the necessity of performing certain operational elements. For instance, if two cuts have been performed on separate machines that are then replaced by one machine to make both cuts at one setting, the handling of the part between the two cuts is eliminated.

b. The reduction of cutting time for certain processes. If a number of cuts have been made separately (but then the arrangement is changed so that all are done simultaneously), the cutting time is reduced from that for the sum of the cuts to that for the longest.

Economic advantages gained from the foregoing arrangements may include one or more of the following reductions:

1. In direct labor; this is the most promising and, usually, the primary objective.
2. In material inventory, by reducing the stock in float or process.
3. In indirect costs of supervision, scheduling, inspection, handling, etc. However, it must never be assumed that there will be a saving in indirect labor or any overhead costs in nearly the same proportion as the saving in direct labor cost. A change in operating methods that results in a change in the amount of required auxiliary services will rarely reduce the over-all costs of those functions in proportion.

Economic disadvantages that may be incurred

Almost invariably when benefits are derived from changes, obligations are incurred to offset them to a certain extent. Cancelling the advantages are the new obligations necessary to provide the improvement. These may include increases in:

1. Fixed charges. Mechanical equipment performing human functions implies a capitalization or storing of productive effort to bring the machinery into existence. Machines which represent combinations are ordinarily more complicated and expensive. Thus, investments are increased and their costs raised accordingly.
2. Material costs in some cases. Higher production rates and setup charges may make it desirable to run larger quantities and thus increase inventories.
3. Floor space. It is conceivable that floor space may be increased in some cases, as well as decreased in others.
4. Indirect costs. Although direct labor may be decreased by automatic machinery, supervision and maintenance costs may be

increased. Special equipment frequently requires attention of a high order.

5. Nonproductive time, necessitated by frequent adjustments and replacements of tools. The fraction of time during which the equipment is gainfully employed may be low in some cases.

How costs are compared

Thus, it is obvious that in the selection of equipment from the standpoint of economy, all the pertinent factors must be taken into consideration. Comparison may be on the basis of annual cost or unit cost. One is more appropriate under some conditions, the second more so in other circumstances. To ascertain the annual costs for two propositions, we set up the expressions for each:

$$C_{A1} = I_{N1}\,(D + R_A + B_A) + C_{D1} + O_1 \tag{26}$$

$$C_{A2} = I_{N2}\,(D + R_A + B_A) + C_{D2} + O_2 \tag{27}$$

and for the comparative unit costs,

$$C_{u1} = \frac{I_{N1}\,(D + R_A + B_A) + C_{D1} + O_1}{N} \tag{28}$$

$$C_{u2} = \frac{I_{N1}\,(D + R_A + B_A) + C_{D2} + O_2}{N} \tag{29}$$

where the subscripts 1 and 2 designate the factors applying to each of two alternates. The remainder of the symbols have the same meanings as defined for Eqs. 22, 24, and 25.

The overhead factors O_1 and O_2 often need not include all the indirect costs, only those which can be expected to change appreciably. Equipment to reduce direct labor does not usually contribute materially towards lowering indirect labor costs. It may, however, call for less floor space and thus provide a lower burden for that reason.

In Eqs. 26 through 29 direct power and similar costs have been omitted because they are usually about the same for comparable units, particularly for machine tools. Material, likewise, is a factor that is not likely to vary from one installation to another to do the same job. Maintenance, also, may be relatively constant, except where one choice is a highly complex machine and the other relatively simple. Yet, there are many cases where these assumed omissions should not be overlooked and discretion must be exercised in every analysis to include all the factors that are necessary.

Curves typical of Eqs. 28 and 29 are shown as 1 and 2 of Fig. 11. For a hypothetical case, equipment number 2 would be chosen for quantities less than E and number 1 for larger quantities. Normally, we do not plot such curves. The quantity N is prescribed by demand and we solve both equations for that specified production to find the lower value of C_U. Machines seldom have the same productive capacity, so it is important that, when two or more are compared, the charges against each be calculated on the basis of the same amount of expected production and not for each machine operating at its full capacity.

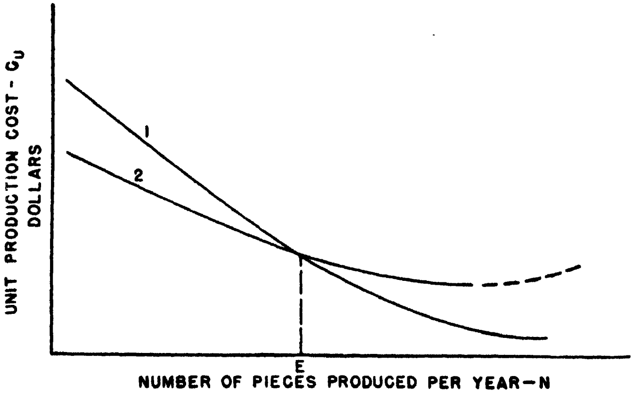

Fig. 11. Unit production costs C_{U1} and C_{U2} of two comparable installations.

After the total charges against each installation have been calculated, it is a simple matter to determine which one shows the lowest total, no matter how many are being compared. So far the discussion has been based on the assumption that each unit of equipment is to be devoted to the manufacture of one article. Similar studies can, however, be made satisfactorily for cases where the equipment is used for a number of different products. The procedure is more complicated but the principles are the same. The difference is that an estimate must be made of the direct and indirect costs for each of the various products. These are added to the corresponding fixed charges to obtain the total amount of cost for each option.

The need for judgment

In most economic problems both tangible and intangible factors are present. Often an appraisal of the measurable elements is not entirely sufficient although it is necessary to provide a sound basis for the exercise of judgment. As pointed out before, obsolescence is not subject to precise predictions. Safety and personal hazards are not easily entered into equations. Many other uncertainties are likely to be present. Careful management and engineering imply thorough scrutiny of the judgment factors. That must not, however, be an excuse for neglect and guesswork.

EXAMPLE 1:[1] A plant furnishing parts to the automotive industry has been making a stud on single-spindle automatic screw machines, with one operator and a helper for each eight machines. The average annual wage of the operator is $3000 and of a helper $2000. Additional screw machines for added capacity would be needed, but the suggestion is made that multiple-spindle automatics be considered instead. The manufacturer of these machines guarantees an output from six of them equal to that of the 32 single-spindle automatic screw machines, but an operator and helper are required for two machines. The price of the multiple-spindle automatic is such that the total investment in six will reach $120,000, whereas the 32 single-spindle machines can be purchased and installed for a total of $96,000.

Either type of machine will be expected to pay out its cost in four years with a 15 per cent return on the average investment. Taxes and insurance are 2 per cent. For average rates, by Eqs. 9 and 10

$$R_A = \tfrac{1}{2} \times 0.15 \times \frac{4+1}{4} = 0.094$$

$$B_A = \tfrac{1}{2} \times 0.02 \times \frac{4+1}{4} = 0.013$$

Thus, for the single-spindle machines, from Eq. 22,

$$C_{F1} = \$96{,}000\ (0.25 + 0.094 + 0.013) = \$34{,}272$$

and for the multiple-spindle automatics, from Eq. 22,

$$C_{F2} = \$120{,}000\ (0.25 + 0.094 + 0.013) = \$42{,}840$$

The annual maintenance cost for a single-spindle machine is estimated to be $250 and power cost $205, as compared with a maintenance cost of $400 and power cost of $385 for a multiple-spindle automatic. Material cost should be the same with either type of equipment. The annual space charge is $75 for a single-spindle machine and $100 for a multiple-spindle automatic. Other overhead need not be distributed as it will not be changed materially by the method employed.

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[1] Adapted from P. T. Norton, Jr., *The Selection and Replacement of Manufacturing Equipment*, Virginia Polytechnic Institute, Bulletin 32, 1934.

The annual charges against the two types of machines can now be tabulated as follows:

Single-spindle Automatic Screw Machines (32)	*Item*	*Multiple-spindle Automatics* (6)
$34,300	Fixed charges (C_F)	$42,840
8,000	Maintenance (M_v)	2,400
20,000	Direct labor (C_D)	15,000
6,560	Power (O_D)	2,310
2,400	Space (O_S)	600
$71,260	Total (C_A)	$63,150

and
$$C_{A1} - C_{A2} = 71{,}260 - 63{,}150 = \$8{,}110$$
saving per year from the multiple-spindle automatics.

Example 2: The dimensions of the part shown in Fig. 12 are being machined on a semi-automatic turret lathe at the rate of 18.50 pieces in a 50-minute hour. Present requirements are for 45,000 of these parts a year, which necessitates running the machine slightly over 48 hours a week. In other words, overtime charges appear likely to cause some increase in the unit cost.

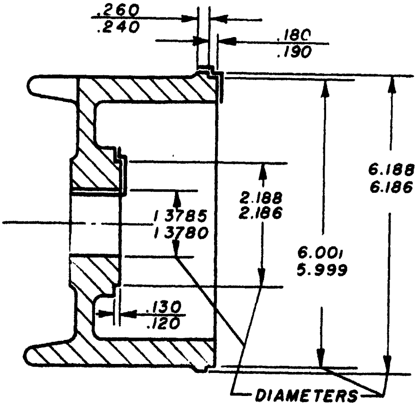

Fig. 12. A sketch of surface finished on a semi-automatic turret lathe.

The present machine is only three years old and it cost $5300 new. A machine tool manufacturer is offering a later model, like that of Fig. 13, which will produce the parts at the rate of 40 pieces in a 50-minute hour, which will provide the required quantity and a margin besides at no overtime cost. The installed cost of the proposed machine and tooling is $6900. The question is whether the proposed replacement will bring about any decrease in unit cost, or whether it would be economical to continue with the present equipment and take care of whatever excess accrues by operating it on an overtime basis.

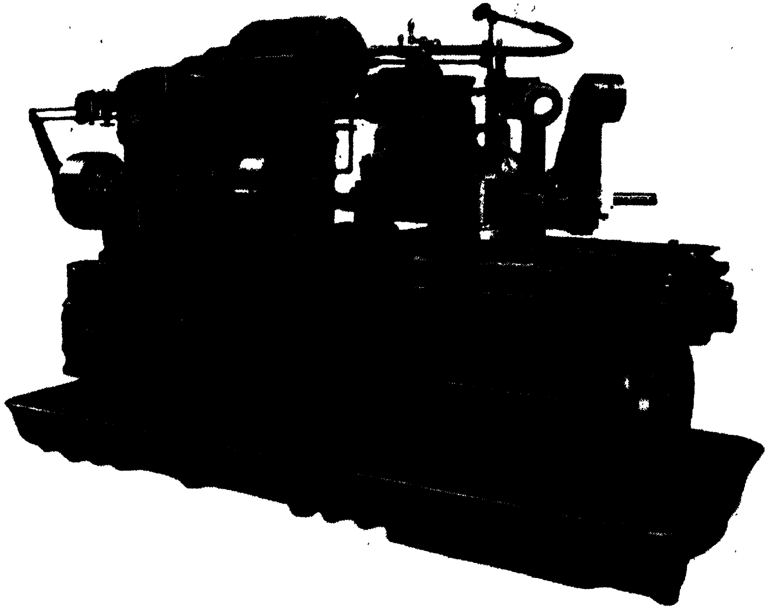

Fig. 13. An automatic turret lathe similar to the one proposed for the part of Fig. 12. (Courtesy Potter and Johnston Co., Pawtucket, R.I.)

Equipment is depreciated on a straight-line basis, and the total length of life of either installation is taken at 10 years. Thus, 7 years of depreciation are left for the present machine on the books, where its value now stands at $3710. Its realizable value is only $3000. Its salvage value, as well as that of the new machine, at the end of a 10-year life, is considered to be only $200. Interest rate is 15 per cent, and the rate for taxes and insurance is 4 per cent.

If the present equipment is denoted by subscript 1 and the proposed by subscript 2:

$$R_{1A} = \tfrac{1}{2} \times 0.15 \times \frac{7+1}{7} = 0.08571$$

$$B_{1A} = \tfrac{1}{2} \times 0.04 \times \frac{7+1}{7} = 0.02286$$

$$D_1 = 0.143$$

$$I_{IN} = 3000 - 200 = \$2800$$

$$\begin{aligned} C_{IF} &= 2800\,(0.143 + 0.086 + 0.023) \\ &= \$705.60 \end{aligned}$$

$$R_{2A} = \tfrac{1}{2} \times 0.15 \times \frac{10+1}{10} = 0.0825$$

$$B_{2A} = \tfrac{1}{2} \times 0.04 \times \frac{10+1}{10} = 0.022$$

$$D_2 = 0.100$$

$$I_{2N} = 6900 - 200 = \$6700$$

$$\begin{aligned} C_{2F} &= 6700\,(0.1 + 0.083 + 0.022) \\ &= \$1373.50 \end{aligned}$$

$$\frac{C_{1F}}{N} = \frac{705.60}{45{,}000} = \$0.0157$$

$$\frac{C_{2F}}{N} = \frac{1373.50}{45{,}000} = \$0.0305$$

Floor space occupied by the two machines is very close to being the same and overhead costs should not be changed materially by the replacement. Maintenance of the present machine is \$200 a year. The new machine will be more complicated, and it is estimated that maintenance may amount to twice as much, or \$400. Thus:

$$\frac{M_{1Y}}{N} = \frac{200}{45{,}000} = 0.0044$$

$$\frac{M_{2Y}}{N} = \frac{400}{45{,}000} = 0.0089$$

For both installations, one man can operate the machine and also give attention to another one. Labor cost is, therefore, charged at 80 cents per hour. Direct power to the present machine is 7 cents per hour, but for the new and more powerful one it will be 10 cents per hour. For present machine, unit direct costs:

$$\frac{80 + 7}{18.5 \times 100} = 0.047$$

For the proposed machine, unit direct costs are:

$$\frac{80 + 10}{40 \times 100} = 0.0225$$

and for total unit costs:

$$C_{U1} = 0.0157 + 0.0044 + 0.047 = \$0.067$$
$$C_{U2} = 0.0305 + 0.0089 + 0.023 = \$0.062$$
$$C_{U1} - C_{U2} = \$0.005 \text{ savings per piece by replacement.}$$

If extra overtime charge on a 40-hour week basis is assumed to be 10 per cent of the unit direct cost of the present method, an additional saving of almost ½ cent can be expected, bringing the total unit saving to a little under 1 cent per piece, or an annual saving of $450. Although this amount is not large and probably less than the inherent error in the estimates, the analysis still indicates that the replacement offering the extra margin of capacity can be made without increasing production costs.

Example 3: Production of 100,000 of the bearing caps of Fig. 14 is contemplated for a year. The labor rate is $1.45 an hour, and overhead is based on a factor of 1.25 times the hourly labor rate, making a total labor and overhead charge of $3.26. On the equipment, the annual interest rate

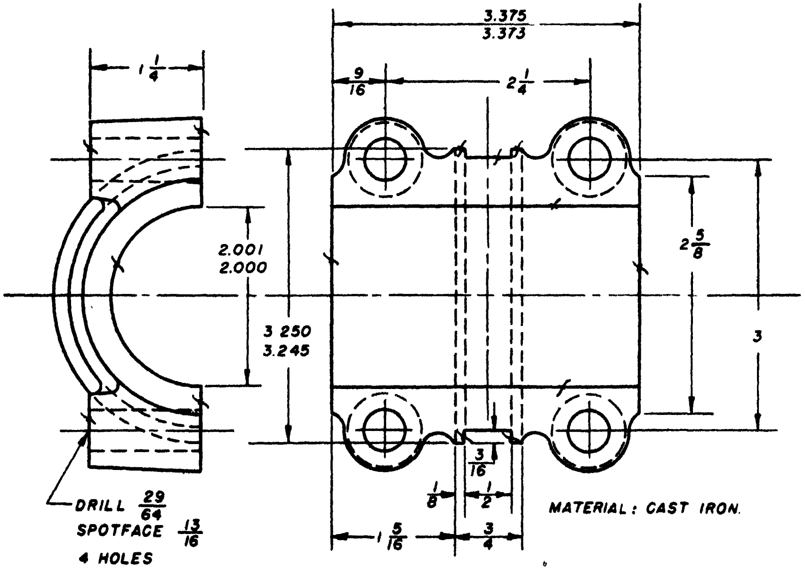

Fig. 14. A front bearing cap.

is set at 15 per cent and insurance and taxes are figured at 4 per cent. The problem to be considered is the method of drilling the four holes of $^{29}/_{64}''$ diameter.

The holes can be drilled, one at a time, in a simple drill jig on a single-spindle drill press. This method offers the lowest fixed investment; but an experienced tool engineer would reject it immediately as being obviously uneconomical for the quantity desired. However, the cost will be calculated to demonstrate the deficiency. With this arrangement the time to drill one piece is 2.86 min. An output of 52,500 parts a year can thus be obtained from one single-spindle drill press and, accordingly, two such machines would be needed. They are standard machine tools and can be depreciated safely over a period of 5 years. Thus:

$$D = 1/5, \qquad R_A = 1/2 \times 0.15 \times 6/5 = 0.09, \qquad B_A = 0.024$$

At $2000 each, the investment in the two drill presses will represent $4000, and

$$C'_F = 4000\,(0.20 + 0.09 + 0.024) = \$1256$$

A simple jig will cost $60, but it will have to be depreciated in one year, so

$$C''_F = 60\,(1 + 0.15 + 0.04) = \$71.50$$

$$C_{1F} = \$1328$$

$$\frac{C_{1F}}{N} = \frac{1328}{100{,}000} = \$0.0133 \text{ per piece}$$

The direct labor and overhead per piece are:

$$\frac{2.86 \times 3.26}{60} = \$0.1554$$

and the total cost per piece

$$C_{U1} = 0.1554 + 0.0133 = \$0.1687 \text{ per piece}$$

A more efficient method requiring a minimum of special equipment utilizes a standard drill press with a four-spindle drill head and a quick-loading cam action jig. The drill press must be heavier than for the first case and will cost $3000, but being a standard machine tool, which can readily be converted to other purposes, it can be depreciated over a period of 5 years. The operation time for this method is 1.04 min per piece, which will give 116,000 pieces per year and require only one machine. Thus:

$$C'_F = 3000 \times 0.314 = \$942.$$

The drill head and jig will cost $350 and will need to be depreciated in one year, so

$$C''_F = 350 \times 1.19 = \$417$$

$$C_{2F} = \$1359$$

and

$$\frac{C_{2F}}{N} = \$0.0136 \text{ per piece}$$

For the second alternative, direct and overhead costs are

$$\frac{1.04 \times 3.26}{60} = \$0.0565$$

and $$C_{V2} = 0.0565 + 0.0136 = \$.0701$$

As a third method a special machine costing $8000 has been proposed. An entirely automatic arrangement would enable the operator to load two parts in one station, while the machine drills two other parts. By this method, the time per piece can be reduced to 0.40 min, with a possible maximum production of 300,000 parts a year. Only one-third of this is needed.

The automatic drilling machine has a high obsolescence rate and must be depreciated in one year, so:

$$C_{3F} = 8000 \times 1.19 = \$9520.$$

$$\frac{C_{3F}}{N} = \frac{9,520}{100,000} = \$0.095$$

Direct and indirect charges are:

$$\frac{.40 \times 3.26}{60} = 0.0218$$

and $$C_{V3} = \$0.117$$

Thus, for the required production of 100,000 parts a year, the second proposal appears most economical.

Problem 1. For the conditions described in Example 3, compute the unit cost for each proposed method for the following production requirements: (a) 5000 bearing caps per year, (b) 10,000, (c) 50,000, (d) 200,000, (e) 500,000, (f) 1,000,000.

Problem 2.[2] Six turret lathes in a brass shop have been engaged in finishing the parts for 250,000 steam-hose-connection assemblies per year. These turret lathes are 20 years old and have a total value of $400 altogether. New turret lathes are proposed for the job. The following production times have been ascertained for new as compared to the old machines.

MACHINING TIME FOR PARTS FOR 100 ASSEMBLIES

	Time in Hours:	
Part	*Old Machines*	*New Machines*
External connection........	1.76	1.15
Swivel....................	1.70	1.10
Tail......................	1.25	.82
	4.71 hrs	3.07 hrs

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[2] This and the following problems are based on case histories collected by National Machine Tool Builders Association, Cleveland, Ohio.

How many new turret lathes would be needed to meet the production requirements?

New turret lathes cost $6500 each but may be depreciated over a 15-year period. The interest rate should be 6 per cent and that for taxes and insurance 4 per cent. The old machines have been depreciated to scrap value so that the fixed charges against them are negligible.

Direct labor is $1.55 per hour. Overhead savings may be ignored, although less space would be required for the fewer new machines.

What should be the total cost for machining the parts for each assembly on the old machines and on the new machines? What annual savings are indicated for the new turret lathes?

Problem 3. The main bearings of an automotive crankshaft have been ground on single-wheel machines, each of which is capable of turning out 60 shafts in an 8-hour day. Four machines have been required to meet production demands for 240 shafts per day. Labor and overhead call for a charge of $4.80 an hour against each machine. There are 250 working days in a year.

A new four-wheel crankshaft grinder is offered at a cost of $48,000 to grind the four main bearings on each shaft at once. One operator can care for the machine and turn out 250 pieces in an 8-hour day. Overhead may be reduced, but that will not be accepted as certain. Therefore, the direct labor and overhead charge against the new machine is also to be $4.80 per hour.

Interest rate can be assumed to be 6 per cent and insurance and taxes 4 per cent. The old machines have little value above that of scrap, which is negligible. The new machine, being a special type, must be depreciated rapidly. Would the investment in the four-wheel grinder show a profit if the cost must be written off in 1 year? If written off in 2 years? In 3 years?

What saving per piece is indicated if depreciation is taken in 2 years? In 3 years?

Problem 4. A part has been turned out on a 2-in. six-spindle automatic at the rate of 43 pieces per hour. 35,000 pieces are needed each month. The machine is seven years old and has a book value of $3600, but a realizable value of only $2500.

A new automatic of the same size and type is proposed. With tooling to produce 114 parts an hour, its cost is $17,461.25. It should be depreciated in seven years.

Direct labor for operating either machine costs $1.20 per hour. No change in overhead is expected. Interest may be taken at 6 per cent and insurance and taxes at 4 per cent.

The new machine offers an additional advantage of being able to do more work, along with that taken over from the old machine. This will save 450 hours per year at a rate of $1.50 per hour previously paid for secondary operations.

What saving per piece and per year is indicated for the new machine?

Problem 5. Six engine lathes in three groups of two each were used for turning crankshafts. They were replaced by two modern contour-forming engine lathes, which cost $23,579 plus tooling of $4000, a total of $27,579. The realizable value of the old lathes was negligible.

From a comparison of the performance records of the old machines with the estimates for the new lathes, the following savings in direct labor were indicated:

78,000	7¼ ft crankshafts per year, average direct labor savings per piece $0.13, total savings...........	$10,140
24,000	"E"-type crankshafts per year, average direct labor savings per piece $0.2167, total savings..	5,200
8,400	"3 cylinder"-type crankshafts per year, average direct labor savings per piece $0.1860, total savings	1,562
Total annual savings in direct labor................		$16,902

The change-over also brought about savings in setup, amounting to $2,866 per year and in tooling costs of $11,000 per year.

Interest may be taken at 6 per cent per year and insurance and taxes at 4 per cent per year.

If the new machines must be depreciated in one year, does the change-over show a profit? If depreciation can be taken over 2 years, is it profitable? Over 3 years, what is the net saving per piece and per year where a profit is shown?

Problem 6. An automotive company has been making 2400 studs per hour on 24 six-spindle automatics operating 16 hours a day to put out a total of 38,400 studs per day. It finds it must increase production to 48,000 studs per day. A manufacturer of single-spindle automatics offers a machine guaranteed to produce 200 of the studs per hour. How many of the single-spindle automatics would be needed to take care of the increased requirements in a 2-shift day of 16 hours, 250 days a year?

The old machines average 10 years in age and have a salvage value of $1000 each. Nineteen of them were rebuilt recently; and if their use is continued, five more will have to be rebuilt immediately at a cost of $6000 each, which may be amortized over a period of 5 years. The new automatics cost $22,000 each and may be depreciated over a 10-year period. The interest rate is 6 per cent and insurance and tax rate 4 per cent. Twelve men are needed to attend the old machines; only one man for every five of the new machines. The direct labor cost is $1.75 per hour and the direct labor dollar overhead rate is one. In addition, a tool saving with fewer machines of $12,960 a year is expected. The spindles of the automatics, old and new, require rebuilding on the average of once a year at a cost of $75 per spindle.

What savings per piece and per year are indicated for the use of the new single-spindle automatics as compared with continued use of the old six-spindle automatics?

PROBLEMS OF EQUIPMENT LIFE

Critical life

The length of time in which an equipment unit can pay for itself over primary costs is often an important criterion. That period is known as the *critical* or *minimum life* and can be found from the relationship:

$$L_{C2}[N(c_1 - c_2) - I_{N2}(r + B)] = I_{N2} - R_{H2} \tag{30}$$

in which

L_{C2} = critical or minimum life in years,
N = number of parts produced per year,
c_1 = all costs, except capital charges, per piece produced on old equipment, in dollars,
c_2 = equivalent costs per piece on new equipment, in dollars,
I_{N2} = net investment in new equipment in dollars,
r = percentage interest rate,
B = percentage insurance and tax rate,
R_{H2} = realizable value of new equipment at end of period in dollars.

Since the expression $N(c_1 - c_2)$ represents a difference in costs, it need not include any overhead items that are substantially unchanged by the replacement. The significance of Eq. 30 is that the entire amount saved by the replacement less unavoidable capital charges are applied and equal to the investment at the end of the minimum period. The actual repayment is shown equal to the net investment minus the estimated amount that could be realized from sale of the equipment at the end of the critical life. This is a questionable refinement. The realizable value is usually comparatively small and it is doubtful that it can be predicted accurately. Usually the results will not be any less accurate if the salvage value is ignored. Current interest, insurance, and tax rates are accepted for this equation rather than average values. The latter would necessarily have to be functions of the dependent variable, L_{C2}, to be accurate and would not be justified in view of the added complexity.

Equation 30 can be simplified and solved for

$$L_{C2} = \frac{I_{N2}}{N(c_1 - c_2) - I_{N2}(r + B)} \tag{31}$$

Critical life standards

In common practice, the consensus of sound management is that critical life should not be more than 3 years. In one survey,[3] eight large corporations reported their policies, and of these, seven favored 1 to 3 years for most machinery; even less than 1 year for single-purpose machines; and only one allowed a critical life of over 3 years.

In another canvass[4] 39 companies reported a definite period, the weighted average of which was about 3 years with only one concern having a period of more than 5 years.

Other concepts of equipment life

But minimum or critical life is not the concept most commonly employed in setting depreciation rates. Corresponding to the two forms of depreciation, functional and physical, are the two periods of *serviceable life* and *physical life*. The first represents the length of time until the machine is overtaken by obsolescence and, therefore, no longer economical to operate. The second represents the period during which the equipment will function satisfactorily before excessive maintenance costs make it unprofitable. This latter can be fairly accurately predicted from past experience, but what the serviceable life of an installation will be is at the best a gamble. Obsolescence arises from too many imponderable sources: style changes, inventions, and economic trends, to state a few.

The length of life of standard machine tools depends partly upon the nature of the tool and the way it is maintained. If kept in good condition, it may often have a value for other purposes after it is no longer applicable to or needed for its original occupation. It is for that reason that it is often desirable to prepare for special jobs by adding auxiliary and specialized attachments to standard machine tools. If the job does not prove permanent, the only loss is in the attachments.

There is a slow, but definite, influence upon the lives of standard machine tools from obsolescence resulting from improvements in later models. This is illustrated by the interaction between cutting tools and machines. At the beginning of this century most machine tools were designed and built for use with relatively low-speed high-carbon tool steel. With the general acceptance of high-speed steel cutting tools prior to and during the First World War, most of that equipment was rendered obsolete. Then in the decades following much of the then newly developed equipment was hastened to obsolescence by the introduction and refinement of cemented-carbide tools, a phase of progress that even today has not reached a climax.

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[3] *American Machinist*, Vol. 65, No. 2 and Vol. 65, No. 7.

[4] P. T. Norton, Jr., *op. cit.*

Equipment life as an index of value

The three criteria of life obviously have a relationship to the risk involved in an investment. The risk is good if the critical life is short in comparison with the probable serviceable life. Both the serviceable and physical lives must be longer than the critical life if the investment is not to be a loss. Also the expense to build a long physical life into any machine or tool is not wisely incurred if the probable serviceable life is of much shorter duration. The ideal life for depreciation is that which is just short of either the serviceable or physical life, whichever is less.

EXAMPLE 4: If 32 single-spindle automatics, having a realizable value of $32,000, are in current use for making studs under the conditions of Example 1, what would be the critical life of six multiple-spindle automatics replacing them? From the standpoint of critical life, would this be a desirable replacement?

From the conditions of Example 1:

$$N(c_1 - c_2) = 36{,}960 - 20{,}310 = \$16{,}650$$

$$I_{N2} = 120{,}000 - 32{,}000 = \$88{,}000$$

$$I_{N2}(r + B) = 88{,}000\ (0.15 + 0.02) = \$14{,}960$$

$$L_{C2} = \frac{88{,}000}{16{,}650 - 14{,}960} = \frac{88{,}000}{1{,}690} = 52 \text{ years}$$

So that although the six-spindle machine might prove profitable as additions, as indicated in Example 1, they are not economical replacements for the present installations.

EXAMPLE 5: The part of Fig. 12, Example 2, was at one time produced at the rate of 12.3 pieces an hour on a turret lathe for an output of 25,000 units per year. One operator per machine was required at a wage of $1.40 per hour. The original cost of the machine had been $3800 and it was now 5 years old, having a realizable value of $1800. Interest was 15 per cent and insurance and taxes 4 per cent. An automatic turret lathe was proposed, at an investment of $5,300. This machine could make 18.5 parts an hour. Overhead, maintenance, and power costs were not expected to change, but only part of a man's time would be required for its attention, so direct labor could be reduced to 70 cents an hour. What would have at that time been the expected critical life?

$$N(c_1 - c_2) = 25{,}000\left(\frac{1.40}{12.3} - \frac{0.70}{18.5}\right) = \$1900$$

$$I_{N2} = 5300 - 1800 = \$3500$$

$$I_{N2}(r + B) = 3500\ (0.15 + 0.04) = \$665$$

$$L_{c2} = \frac{3500}{1900 - 665} = 2.84 \text{ years}$$

an attractive promise of return, even without the later increase experienced in production.

Problem 7. What is the critical life of the new turret lathes proposed in Problem 2 for machining the parts for the steam hose connection assemblies?

Problem 8. What is the critical life of the new four-wheel crankshaft grinder offered in Problem 3?

Problem 9. What is the critical life of the new automatic proposed in Problem 4?

Problem 10. Estimate the critical life of the two modern contour-forming engine lathes described in Problem 5.

Problem 11. Estimate the critical life of the single-spindle automatics offered in Problem 6 to replace the multiple-spindle automatics for making studs.

Limitations imposed on physical life by upkeep costs

Many standard and general-purpose machine tools, such as tool-room lathes and drill presses, are little affected by functional depreciation over reasonable periods of time. Their economic life is rather a matter of how long they can be operated before maintenance costs become excessive. If

I = original cost of machine tool in dollars,
X = number of years it is used,
I/X = yearly cost of the original investment on a straight line basis.

Also, if

M = total cost of maintenance during the life of the machine, in dollars,

M/X is the average cost per year of maintenance, and the total average annual cost of operating the machine for an assignable period in years is, therefore,

$$C_A = IB + \frac{I}{X} + \frac{M}{X} + C \tag{32}$$

where

B = annual percentage of interest, insurance, and taxes, assumed constant,
C = annual overhead and direct charges, assumed constant.

A minimum can be found for C_A, and the corresponding value of X designates the number of years for which it is most economical to operate the machine.

From the typical equipment cost curve of Fig. 9 the maintenance cost, y, at any time is a function of that time, x, or

$$y = f(x) \tag{33}$$

and

$$M = \int_0^x f(x)dx \tag{34}$$

and

$$C_A = IB + \frac{I}{x} + \frac{\int_0^x f(x)dx}{x} + C \tag{35}$$

$$\frac{dC_A}{dx} = -\frac{I}{x^2} + \frac{x[f(x)]_0^x - \int_0^x f(x)dx}{x^2} = 0$$

$$I = xf(x) - xf(0) - \int_0^x f(x)dx \tag{36}$$

$$= xy - \int_0^x f(x)dx$$

For simplicity, most depreciation curves can be closely approximated over the life of the property by a straight line, as in Fig. 10. For such a case,

$$y = bx$$

$$\int_0^x f(x)dx = b\int_0^x x\,dx = bx^2/2$$

and $$I = bx^2 - \frac{bx^2}{2} = \frac{bx^2}{2}$$

from which $$x = \sqrt{\frac{2I}{b}} \tag{37}$$

Thus, for such a case it is not economical to maintain the machine for a life longer than $\sqrt{\frac{2I}{b}}$ years. Additional service will necessitate an average yearly cost larger than that already experienced, but it may be expected that the same minimum economy will be realized from the same type of new equipment operated under the same conditions. From the analysis it is evident why it is not considered good policy to overhaul low-cost tools, such as small drill presses, but rather to get rid of them and purchase new ones when expensive repairs become necessary.

EXAMPLE 6: A lathe cost $4000 when it was purchased new. During its life maintenance costs have been increasing at the approximate rate of $80 per year and experience with similar machine tools indicates that they will continue to rise at about the same rate. Thus

$$b = 80$$

and $$x = \sqrt{\frac{2 \times 4000}{80}} = 10 \text{ years}$$

Or, at the end of its tenth year, the lathe should be replaced.

Problem 12. The upkeep expenditures on a drill press have been rising uniformly from zero along a straight line. For the tenth year of its life that has just passed, $275 has been spent on maintenance for it. Its new cost was $2000, about the same that a replacement would cost now. Is it time to buy a new drill press? If not, when should one be considered, if maintenance costs continue along the same trend in the future?

Problem 13. A lathe cost $10,200 new. During its life maintenance costs have risen at the rate of about $50 per year. What should be an economical physical life for that lathe?

ECONOMY OF TOOLING

The basic problem

So far, we have been discussing the general application of certain economic principles to all forms of manufacturing equipment. Each type of application calls for a somewhat different treatment of the formulas and factors. The tool engineer is particularly interested in the application of the principles to jigs, fixtures, gages, cutting tools, and dies. Professor J. W. Roe developed simple formulas for that purpose.[5] He has stated that the problem is found in one or more of the following questions:

1. How many pieces must be run to pay for a fixture of given estimated cost that will show a given estimated saving in direct labor cost per piece? For instance, how low a run will justify a fixture costing $400 to save 3 cents on direct labor cost of each piece?
2. How much may a fixture cost that will show a given estimated unit saving in direct labor cost on a given number of pieces? For instance, how much can be put into a fixture to "break even" on a run of 10,000 pieces, if the fixture can save 3 cents on the direct labor cost of each piece?
3. How long will it take a proposed fixture, under given conditions, to pay for itself, carrying its fixed charges while so doing? For instance, how long will it take a fixture costing $400 to pay for itself if it saves 3 cents on direct labor cost per unit, production being at a given rate?
4. What profit will be earned by a fixture of a given cost for an estimated unit saving in direct labor cost and given output? For instance, what will be the profit on a $200 fixture if it will save in direct labor cost 3 cents a piece on 10,000 pieces?

Symbols for tooling

To simplify tooling formulas, the factors for power cost and displaced equipment value are omitted, and other factors are treated as constants. The symbols used in these equations are:

N = Number of pieces manufactured per year. (It must be remembered that N is not the number of pieces per run unless the tooling is intended for a single run of less than a year's duration.)

A = yearly percentage interest rate on investment (average interest rate, R_A, may be used if desired; but since the life is usually short, often one year and seldom much more, the difference will probably be negligible).

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[5] J. W. Roe, "Principles of Jig and Fixture Practice," *Mechanical Engineering*, Feb. 1941, Vol. 63, No. 2, p. 117.

B = yearly percentage allowance for insurance and taxes.
M = yearly percentage allowance for upkeep and maintenance.
$D = 1/L$ = annual percentage depreciation allowance on a straight-line basis, where L is the number of years required for amortization of investment out of earnings.
I = estimated cost of the fixture, jig, etc.: i.e., cost installed and ready to run, including drafting and toolroom time, material, and toolroom overhead, in dollars.
y = yearly cost of setups in dollars. This factor should include expenses for taking down the apparatus and putting machine into normal condition, cost of issuing orders, and overhead chargeable during setup.
s = savings in unit direct labor cost $= C_{D1} - C_{D2}$.
T = yearly total saving in labor overhead, in dollars,
= St, where
S = yearly saving in direct cost of labor, in dollars
t = rate of overhead on the labor saved (direct labor dollar overhead rate, R_{LD})
V = yearly gross operating profit in excess of fixed charges, in dollars.

Formulas for tooling

For an even break, the annual operating savings must equal the total fixed charges and setup costs for that period.

$$Ns(1 + t) = I(A + B + M + D) + y$$

and
$$N = \frac{I(A + B + M + D) + y}{s(1 + t)} \tag{38}$$

from which
$$I = \frac{Ns(1 + t) - y}{A + B + M + D} \tag{39}$$

and
$$V = Ns(1 + t) - y - I(A + B + M + D) \tag{40}$$

and
$$L = \frac{I}{Ns(1 + t) - y - I(A + B + M)} \tag{41}$$

Treatment of factors

In any one plant, the items A, B, M, and D can usually be considered constants over certain periods conforming to policy and can be combined into a single factor for convenience. As for depreciation, a prominent tool manufacturer[6] has recommended, in line with prevailing practice, that standard tools—which can be used interchangeably—can safely be depreciated in approximately 2 years; but that special tools—applicable to only one job, model, or product—should have a depreciation period of one year, one season, or one model. Perishable tools which wear away with use should be taken into account and charged for in accordance with their expected impermanence.

Example 7: To illustrate an economy analysis, the following cases have been adapted on the basis of these conditions:

s = estimated unit saving in direct labor cost = 3 cents
t = percentage overhead on labor saved = 75%
y_1 = estimated cost of each setup = \$15
A = interest rate at 6% = 0.06
B = rate for insurance and taxes at 4% = 0.04
M = maintenance ratio = 0.10
L = life of tools estimated = 2 years
$D = 1/L$ = depreciation rate = 0.50
$A + B + M + D = 0.70$

1. If the fixture is estimated to cost \$400, how many pieces must be made on it in one lot each year to save its cost in 2 years?

$$N = \frac{400 \times 0.70 + 15}{0.03\ (1 + 0.75)} = 5620 \text{ pieces}$$

2. If the product is manufactured in 5 lots per year, how many pieces must be made each year to earn the cost of the fixture in 2 years?

$$N = \frac{400 \times 0.70 + 75}{0.03\ (1 + 0.75)} = 6762 \text{ pieces}$$

As is evident, the increased cost from a larger number of setups requires more pieces. As will be shown later, this may be justified by other savings.

3. If the fixture is intended for a single lot, how large must that lot be? The running of the lot will probably not require even one year, so $D = 1$, and $A + B + M + D = 1.20$ and

$$N = \frac{400 \times 1.20 + 15}{0.03\ (1 + 0.75)} = 9427 \text{ pieces}$$

Thus, fewer pieces need be run in one lot to pay for the fixture than would be required altogether in two lots extending over 2 years, as a comparison of parts 1 and 3 of this example shows. That is true because for the single run there is one less setup and overhead is carried for only one year.

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[6] Charles T. Stilwell, President of Warner and Swasey Company, as reported by C. P. Alford and J. R. Bangs, *Production Handbook*, p. 875. New York: The Ronald Press Co., 1947.

4. How much can be invested in the fixture for a single lot of 9427 pieces?

$$I = \frac{9427 \times 0.03\,(1 + 0.75) - 15}{1.20} = \$400$$

5. How much can be invested in a fixture that is to be used for 6762 pieces each year divided into 5 lots to be run over a period of 2 years?

$$I = \frac{6762 \times .03\,(1 + 0.75) - 75}{0.70} = \$400$$

6. In how long a time will a fixture costing $400 pay for itself if 6762 pieces are to be run each year in five lots in accordance with the original conditions of this problem?

$$L = \frac{400}{6762 \times 0.03\,(1 + 0.75) - 75 - 400\,(0.20)} = 2 \text{ years}$$

7. If the fixture of part 6 can be made for $250, instead of $400, adequate for the job, what profit is to be expected?

$$\begin{aligned} V &= 6762 \times 0.03\,(1 + 0.75) - 75 - 250\,(0.70) \\ &= 355 - 75 - 175 = \$105 \text{ a year} \end{aligned}$$

8. If the fixture can be made for $250, instead of $400, and is to be used for a single lot of 9427 pieces, what profit may be expected?

$$\begin{aligned} V &= 9427 \times 0.03\,(1 + 0.75) - 15 - 250\,(1.20) \\ &= 495 - 15 - 300 = \$180. \end{aligned}$$

9. How much money can be put into a fixture for a single lot of 2500 pieces if it will save 3 cents per piece and entail a setup cost of $15?

$$I = \frac{2500 \times 0.03\,(1 + 0.75) - 15}{1.20} = \$96.90$$

These examples illustrate how various tooling decisions can be reached. They apply not only to jigs and fixtures but also to dies, gages, cutting tools, and special equipment. The systematic use of these principles as a basis for the authorization of tooling expenditures above a set minimum amount cannot be overemphasized. Also, preliminary studies to be continually effective should be checked by actual results. If nothing more, such a procedure will provide evidence of the quality of the tool engineering. If expectations are consistently not realized, steps can be indicated to improve the situation. If results are good, a means will be provided to place the accomplishments favorably before the management.

Problem 14. A part has had a hole to be drilled in it located by layout and center punching. The time for locating the hole can be reduced by 0.5 min per piece if a jig is provided. For a labor rate of $1.20 an hour, this means a saving of 1 cent a piece. The percentage overhead on labor saved is 100 per cent. Setup time is no more with than without the jig. Interest rate is 6 per cent, the rate for insurance and taxes 4 per cent, and maintenance ratio 25 per cent.

If the cost of the jig is $75, (a) how many pieces must be run in one lot to make it worth-while? (b) How many pieces must be made on the jig in one lot each month to earn the cost of the jig in 2 years? (c) How many pieces must be made on the jig in one lot each year to save its cost in 2 years?

If only 2500 pieces are to be made during the coming year, and they must pay for the jig, how much can be spent for it?

Problem 15. A cup has been blanked in one die and formed in another. The labor cost has been 85 cents per 1000 pieces for each operation. The dies must be renewed and a progressive die to do both steps in one press stroke is proposed. Assume that this will cut the labor cost in half. The progressive die will cost $150 more than both separate dies. Setup cost for the progressive die will be $10 more. The following conditions also apply:

Interest rate = 0.10
Insurance and taxes = 0.03
Maintenance rate = 0.15
Direct labor dollar overhead rate = 0.50

If the extra cost must be paid out of one run, how many pieces must be made in it?

If five lots are to be run during the year in which the cost of the die must be realized, how many pieces must be in each lot?

Problem 16. 300,000 pieces a year are blanked in six batches for a certain part. When the strip is hand-fed, the labor cost is 60 cents per 1000 pieces. If a roller feed is used, this labor cost can be cut in half. Also,

Interest rate = 0.15
Insurance and tax rate = 0.05
Maintenance rate = 0.10
Overhead rate = 0.50
Life of roller feed = 2 years.
Extra cost of setup with roller feed = $15 for each setup.

What amount of the cost of the roller feed attachment can be charged off to this job?

Problem 17. The "hole spacer" shown in Fig. 230 is used to position holes accurately and quickly under the spindle of a drill press. It is set for any particular job to repeat the settings as often as desired. When one job is finished, the device can be easily reset for another. For small and moderate quantities, the versatility of this device makes it a profitable substitute for special jigs. An interesting problem is the determination of the quantities for which this attachment is more economical than jigs.

(a) The cost of the 30-in. × 20-in. hole spacer, including freight and installation, is about $9000. The investment may be depreciated over

5 years, since it is a standard item. Interest rate is 15 per cent and taxes and insurance 4 per cent. Assume that there is enough work to keep the device busy for 1500 hours during a year. What is the hourly return that must be charged on the investment?

(b) For any part that has one or more holes to be drilled, there is now the choice of making a special jig or putting the work on the hole spacer. In either case the same kind of drill press must be used. The direct time for the job is about the same using either device. Setup time will probably be longer with the hole spacer, but the larger the number of pieces, the smaller the differential per piece. Thus, the difference in setup time may be safely ignored. The problem is one of finding the number of pieces of the part in question for which the fixed charges on the hole spacer are less than those for a special jig, and vice versa. Derive an expression of the number of pieces N for which the fixed charges on the spacer just equal those for a jig, in terms of m, the time to machine each piece, and I, the cost of the jig.

(c) For one part a jig will cost \$450 for 10 holes. Machining time is 1¼ hours per piece. Up to how many pieces is it economical to use the hole spacer?

(d) For one part a jig will cost \$125 for seven holes. Machining time is 15 minutes per piece. Up to how many pieces is it economical to use the hole spacer?

(e) For one part a jig will cost \$60 for three holes. Machining time is 10 minutes per piece. Up to how many pieces is it economical to use the hole spacer?

ECONOMIC LOT SIZE

The influence of lot sizes on tooling

Lot size is sometimes a basic consideration of the tool engineer's calculations. In connection with total production requirements, the sizes of the lots to be run determine the number of setups to be made. Small lots and frequent setups favor methods using general-purpose and versatile machine tools, simple and easily set up jigs and fixtures, hand feeds, and a minimum of operations. Large lots allow greater expenditures for semi-automatic or automatic tooling. Normally, the determination of production schedules and lot sizes is not within the province of the tool engineer. He may be able to obtain the information he needs on that score from others in his organization whose responsibility it is to set the production schedules or he may find it available in the plant records. Sometimes though, he must provide his own forecast in the preliminary stages of a project.

The factors to be considered

Economic lot size problems may be solved in several different ways and a number of formulas have been developed for that purpose. In some, an attempt has been made to include every variable that has any effect upon the general problem, with the result that they are very complicated. Simplified formulas are also available, but one runs the risk of securing incorrect results unless he understands the fundamental reasoning in their derivation. Let

Q = the lot size (pieces per lot),
Q_m = the minimum lot size (pieces per lot),
Q_p = the practical lot size (pieces per lot),
C_p = total preparation cost per lot (dollars) including cost of issuing orders, setting up the machine, and overhead and fixed charges for the time of setup.
P = pieces made per day,
U = pieces used per day,
N_y = number of days worked per year,
C_M = manufacturing cost per piece, including direct labor, materials, and overhead cost but not preparation cost,
S_y = cost of storing one piece for one year (dollars),
R_1 = annual fixed charge percentage (taxes and insurance) against the investment in finished inventory,
R_2 = desired return on capital, per cent,
C_u = total amount charged against each piece (dollars) for (a) preparation costs, (b) direct costs, (c) storage charges.

The solution of the problem

Two assumptions can be made without affecting the results materially. First, the total amount of direct costs per piece is charged from the moment production begins. Second, the preparation cost per piece is not subjected to capital charges during storage. Also, it is convenient to assume that the consumption rate is uniform.

The maximum amount of capital tied up in finished inventory will be C_MQ dollars, and the average amount of capital thus tied up will be $C_MQ/2$ dollars. For N_yU pieces per year, the average amount tied up for one piece will be $C_MQ/2N_yU$ dollars.

The charges against the finished inventory awaiting sale or assembly (for taxes and insurance) in dollars per piece = $R_1C_MQ/2N_yU$.

Likewise, the similar inventory interest charge in dollars per piece = $R_2C_MQ/2N_yU$.

A charge must also be made for rental or storage space occupied by the finished article. Although this is not true for all products, some must have space reserved for any part sufficient to take care of the maximum number placed in storage, especially if they are stored on special racks or in bins. There will be placed in storage each day during production $P - U$ pieces. Production will continue for Q/P days so that storage must be provided for $Q/P\ (P - U)$ or $Q(1 - U/P)$ pieces. Where P is much larger than U, the number for which storage must be provided is practically Q. As it costs S_y dollars to store one piece for one year and N_yU pieces are used per year, the unit cost of storage space in dollars equals

$$\frac{S_y\left(1 - \frac{U}{P}\right)Q}{N_yU}$$

The total charges per piece incident to storage can, therefore, be expressed as:

$$\left[\frac{(R_1 + R_2)C_M + 2\,S_y\left(1 - \frac{U}{P}\right)}{2\,N_yU}\right]Q$$

For simplicity, let the terms in brackets be expressed by the symbol k. The total charges against each piece will be

$$V = \frac{C_P}{Q} + C_M + kQ \tag{42}$$

where

$\frac{C_P}{Q}$ is the unit preparation cost,

C_M is the unit manufacturing cost,

kQ is the unit storage cost.

The economical lot size will be that for which V is a minimum:

$$\frac{dV}{dQ} = -\frac{C_P}{Q^2} + k = 0$$

from which

$$Q_m = \sqrt{\frac{C_P}{k}} \tag{43}$$

The equation for minimum lot size can also be written in the form

$$\frac{C_P}{Q_m} = kQ_m \tag{44}$$

which expresses the fact that for the economic lot size, the unit preparation charges are equal to the unit storage charges.

EXAMPLE 8:[7] Assume the following conditions:

$C_P = \$10$,
$P = 1000$ pieces per day,
$U = 100$ pieces per day,
$N_y = 300$ days per year,
$C_M = \$0.10$ per piece,
$S_y = \$0.001$ per piece per year,
$R_1 = 0.03$ per year,
$R_2 = 0.20$ per year,

then

$$k = \frac{(0.03 + 0.20)/10 + 2(0.001)\left(1 - \frac{100}{1000}\right)}{2(300)(100)} = 4.1 \times 10^{-7}$$

and from equation (43)

$$Q_m = \sqrt{\frac{10}{4.1 \times 10^{-7}}} = 10^4\sqrt{0.244} = 4940 \text{ pieces}$$

The wide choice of lot sizes

The way that the unit cost varies with lot size for the conditions of Example 8 is charted in Fig. 15. Of particular significance is the evident fact that the unit cost is very near the minimum, over a wide range of lot sizes. The relationship is not exactly the same for different conditions, but in general it is very broad. To decrease the unpredictable risks of obsolescence, the lot size can and often is reduced below the most economic figure without any appreciable increase in unit cost. On the other hand, if the economies of tooling can be benefited by larger lot sizes, there is latitude for them. This is the most important idea that the tool engineer can get from the study of economic lot sizes.

Problem 18.

Let the total preparation cost = \$61.80.
The number of pieces made per day = 47.

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[7] Adapted from P. T. Norton, Jr., *Economic Lot Sizes in Manufacturing*, Virginia Polytechnic Institute, Bulletin 31, 1934.

The number of pieces used per day = 20.
The number of days worked per year = 250.
The manufacturing cost per piece = \$6.07.
The cost of storing one piece for one year = \$0.05.
Tax and insurance rate = 0.04.
Interest rate = 0.15.

(a) Find the minimum lot size; (b) ascertain the unit cost for lot sizes of 200, 500, 800, 1100, 1400, 1700, and 2000 pieces.

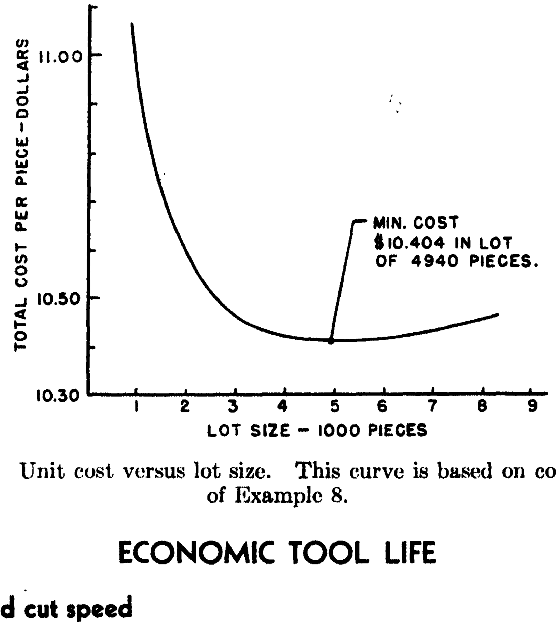

Fig. 15. Unit cost versus lot size. This curve is based on conditions of Example 8.

ECONOMIC TOOL LIFE

Tool life and cut speed

The length of life of any cutting tool has been shown by many investigators to be related to the speed at which the tool is run by the empirical equation:[8]

$$VT^n = K_m \tag{45}$$

where

V = cutting speed in feet per minute,
T = tool life or duration of cut between grindings, in minutes,
K_m = cutting speed constant corresponding to 1 min of tool life,

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[8] For more detailed information on this relationship, as well as values for actual conditions, see texts and treatises on metal cutting, of which several are referred to in the bibliography of this chapter.

depending for its value on composition, form, size and treatment of the tool, the work material, the size and shape of the cut, and the cutting fluid.

n = a constant exponent depending upon the conditions under which the tool is run, such as the material and shape of the tool, size of cut, material cut, and cutting fluid.

This relationship alone is not enough to specify the most desirable speed at which to run a tool. It does show that if a tool is run very fast, so that it removes metal quickly as long as it is cutting, the benefit from the tool will be short lived. At the other extreme, a tool will last a long time if it is run slowly enough, but will be inefficient. The most desirable speed is that which delivers the most output for each dollar spent on the operation which the tool performs. For that, costs must also be considered.

The costs of metal cutting

The costs of operating a cutting tool include not only those occurring while the tool is cutting but also others which must be met to keep the operation going. While a tool is cutting, the charges which vary with the length of cut are determined by the rate

$$R_1 = \frac{C_{D1} + R_B}{60} \tag{46}$$

where

R_1 = the rate charged against the operation while the tool is cutting in dollars per minute,

C_{D1} = the direct labor rate on the machine in dollars per hour,

R_B = burden rate or machine hour rate in dollars per hour. In this connection all overhead charges, including fixed charges, should be included.

To keep the operation going, the costs which must be charged against the tool but occur while it is not in use include:

$$C_2 = \frac{t_1}{60}(C_{D1} + R_B) + \frac{t_2}{60}(C_{D2} + R_t) + C_t \tag{47}$$

where

t_1 = the time the machine must be idle for setting and removing the tool, in minutes,

t_2 = the time to resharpen, dress, and otherwise restore the tool, in minutes,

C_{D2} = the direct labor rate to restore the tool to usable condition, in dollars per hour,

R_t = the overhead rate of the equipment or department in which the tool is restored, in dollars per hour,

C_t = cost of the tool material consumed in one resharpening, in dollars.

The tool life for lowest cost

The amount of metal removed by a tool between grinds is

$$Q = F \times d \times W \times T \tag{48}$$

where

F = feed, in inches per minute,

d = depth of cut, in inches,

W = width of cut, in inches (in the case of a turned diameter this is equivalent to the mean circumference of the cut),

T = tool life, in minutes.

For a definite feed, the metal removal, in cubic inches per tool,

$$Q = MVT \tag{49}$$

where

M = a constant taking into account the feed in inches per revolution or per stroke, and the depth of cut, and factors to bring out proper units,

V = cutting speed in feet per minute.

The measure of performance of a tool is the amount of metal it removes, in cubic inches, per dollar of cost. This may be expressed by

$$\begin{aligned} U &= \frac{MVT}{TR_1 + C_2} \\ &= \frac{K_m M T^{(1-n)}}{TR_1 + C_2} \end{aligned} \tag{50}$$

This last expression is obtained by substituting $K_m T^{-n}$ for V. Performance is best when

$$\frac{dU}{dT} = \frac{(TR_1 + C_2)(1 - n)K_m M T^{-n} - K_m T^{(1-n)}(R_1)}{(TR_1 + C_2)^2} = 0$$

or

$$(TR_1 + C_2)(1 - n) = R_1T$$

and

$$T = \frac{1 - n}{n}\frac{C_2}{R_1} \tag{51}$$

or

$$T = \frac{1 - n}{r}\frac{\frac{t_1}{60}\,(C_{D1} + R_B) + \frac{t_2}{60}\,(C_{D2} + R_t) + C_t}{\left(\frac{C_{D1} + R_B}{60}\right)} \tag{52}$$

From equation (45),

$$V = K_m\left(\frac{1 - n}{n}\frac{C_2}{R_1}\right)^{-n} \tag{53}$$

The qualifications of economic tool life

Equation 51 may be written $TR_1 = [(1 - n)/n]C_2$. This means that the greatest economy of tool life is realized in an operation when TR_1, the cost incurred when the tool is cutting, is equal to $(1 - n)/n$ times the costs, C_2, which occur while the tool is not cutting.

Equations 52 and 53 reveal why there can be so much difference, as there is, among recommended cutting speeds for certain purposes in handbooks and other references and from one factory to another. The factor t_1 of Eq. 52 represents the time needed to set the tool in position on the machine. Obviously, that is going to be more for a finishing operation in which close limits must be observed than for a roughing operation. The time to resharpen and dress a tool, represented by t_2, is going to be more for one type or form of tool than another. The direct charges and overhead for a particular machine may be different from those for another machine. Also, the facilities and costs of resharpening cutters vary from plant to plant, and even within one plant. In a small factory, a special setup may have to be made each time a milling cutter must be sharpened, but in a large plant it may be profitable to keep one or more cutter grinders set up for milling cutters. For so many variables, it is evident that no published tables of cutting speeds can be relied upon for even the majority of cases.

Exact calculations to determine economical cutting speeds are very seldom attempted for production. The difficulty in forecasting and ascertaining precisely the values of all the necessary factors precludes any such trial. In practice an effort is made to arrive at economical cutting speeds by estimating the influence of the various factors and approximating a fair balance for them. An understanding of the factors and how they affect the results can be gained from a study of the ideal conditions.

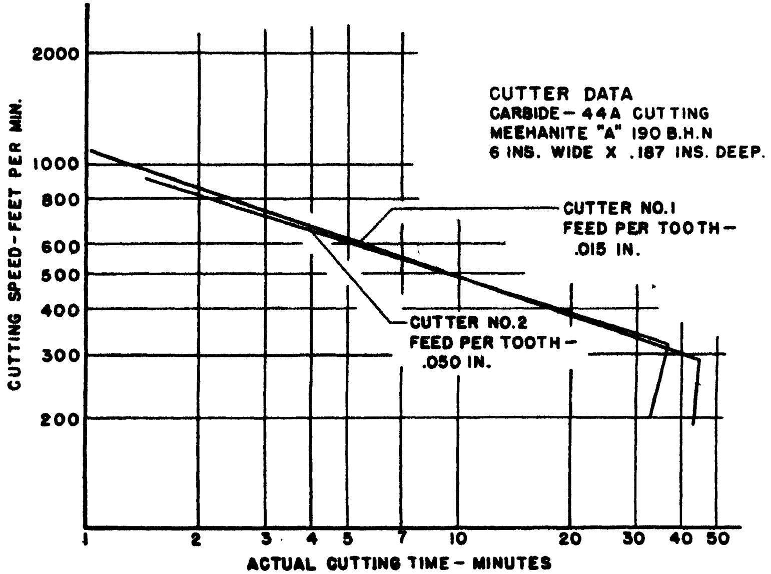

Fig. 16. Speed and cutter life of two milling cutters. (Adapted from "Milling Cast Iron with Carbides," *Report from Cincinnati Milling*, Sept.-Oct. 1945, Vol. 2, No. 5.)

Example 9:[9] A surface 6 in. wide and 20 in. long is milled to a depth of $^3/_{16}$-in. in Mechanite "A" iron, having a 190 B.H.N. The 10-in. diameter cutter has 12 teeth of 44A carbide with angles +3, +3, 30, +4. The feed rate is 0.015 in. per tooth. Tests showed

$$VT^{0.354} = 1098$$

in accordance with the line for cutter number 1 of Fig. 16. This holds true only for a cutting speed above about 300 s.f.p.m. It is known that at low speeds carbides do not stand up. In this case the tool life is shorter below than above 300 s.f.p.m.

The following cost data apply to the operation:

Direct labor cost on milling machine, C_{D1} = \$1.00/hour
Overhead on milling machine, R_B = \$4.00/hour

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[9] Data based upon that given in "Milling Cast Iron with Carbides," *Report from Cincinnati Milling*, Sept.-Oct. 1945, Vol. 2, No. 5, p. 17.

Direct labor cost on cutter grinder, C_{D2} = \$1.00/hour
Overhead on cutter grinder, R_t = \$1.25/hour
Time to change and reset cutter, t_1 = 10 min
Time to resharpen cutter (part of t_2) = 120 min
Time to rebraze cutter (part of t_2) = 60 min
Cutter reground 4 times between rebrazing; teeth replaced after being reset 3 times. Teeth cost \$2.00 each. Thus:

$$R_1 = \frac{1+4}{60} = \frac{1}{12}$$

$$C_2 = \frac{10}{60}(1+4) + \frac{120+15}{60}(1+1.25) + \frac{2 \times 12}{12} = \$7.897$$

and $$V = 1098\left(\frac{1-0.354}{0.354} \times 7.897 \times 12\right)^{-0.354} = 177.23 \text{ ft/min.}$$

This cutting speed is below 300 ft/min, and the corresponding tool life would actually be less than the maximum of 45 min indicated by the curve of Fig. 16. This case is an example of one where the mathematical interpretation must be modified to conform to the circumstances. Equation 50 shows that the economic performance of this milling cutter drops off at higher speeds. Thus, a little less than 300 ft/min is the most economical speed as it provides the longest tool life on the curve.

Another consideration may be that of getting a higher rate of production, even at a larger unit cost. Further analysis shows, for instance, that if the cutting speed is increased to 500 ft/min, production is increased 28 per cent with a rise in unit cost of only about 6 per cent.

Problem 19. Cutter No. 2 of Fig. 16 is put on the job described in Example 9. It is fed at a rate of 0.050 in. per tooth, and has a maximum life of 37 min at a little over 300 s.f.p.m. It is subject to the same costs as cutter No. 1. At what speed should it be operated for most economical performance?

Problem 20. A H.S.S. lathe tool cutting SAE 2340 steel is found to be governed by the relationship

$$VT^{0.111} = 200$$

The direct labor rate is \$1.50 per hour and machine rate \$2.25 per hour. The operator grinds his own tools, and the machine charges go on while he does so. What is the economic cutting speed if the time to grind and reset the tool is (a) 1 min, (b) 5 min, (c) 10 min?

The cost of the tool material may be considered small enough to be neglected.

Problem 21. In a certain plant, direct labor costs \$1.75 per hour. The overhead on the lathe is \$2.35 per hour and on the cutter grinder \$1.50 per hour. The time to regrind and redress each tool is 15 min and to reset a tool in the machine is 1 min. The tungsten carbide tools cost \$6.25 new and are good for ten grinds each. Find the economic tool life and cutting speed for the following conditions:

No.	Material	Depth of Cut	Feed	For $VT^n = C$	
				n	C
1	SAE 1040	0.062	0.025	0.156	800
2	SAE 1060	0.125	0.025	0.167	660
3	SAE 1060	0.187	0.025	0.167	615
4	SAE 1060	0.250	0.025	0.167	560
5	SAE 1060	0.062	0.021	0.167	880
6	SAE 1060	0.062	0.042	0.164	510
7	SAE 1060	0.062	0.062	0.162	400
8	SAE 2340	0.062	0.025	0.162	630

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4 PLANNING AND TOOLING FOR ECONOMY

GENERAL PRINCIPLES

The meaning of planning for economy

As has been stated, the tool engineer's responsibility in planning a process and its tooling includes obligations to assure:

1. Maintenance of the required effects.
2. Accomplishment of the required results in the most economical manner. This second consideration is the aim of planning for economy.

Economy, in any case, means getting the desired results at the lowest unit cost. This involves two factors: the amount spent and the return received. For an optimum return, expenses must be as low as possible. For a necessary expenditure, arrangements must be made for the greatest output.

Production costs are classified as direct, indirect, and fixed. Economy is concerned with minimizing all three in the following ways:

1. Labor is the direct cost offering the most opportunity for savings. Labor rate may be reduced by lowering the grade of skill needed for a job. The amount of labor consumed for a task may be decreased by shortening the time or decreasing the exertion required.
2. Indirect costs of upkeep, reconditioning, and repairs must not be overlooked. There are many ways in which tools can be arranged to minimize these items. Supervision may be relieved as the need of attention is reduced. As the direct labor load is decreased, many indirect costs are reduced.
3. Fixed costs are alleviated by minimizing initial expenditures for physical equipment.

The elements of an operation

The objective of finding the least time to do an operation is realized through analysis of its elements. Any manufacturing task can be broken down into four universal acts: (1) Get. (2) Place. (3) Process. (4) Dispose.

Each of these acts is made up of a number of elements. Just exactly what the elements are called in any case is a matter of convenience. Thus, for a milling operation, the elements might be: (1) Pick up. (2) Load. (3) Clamp. (4) Position. (5) Mill. (6) Retract. (7) Unclamp. (8) Unload. (9) Deposit. (10) Clean.

Pick up refers to the time required to take the piece from a pile or pan and carry it to the fixture.

Load is the time to position the workpiece in the fixture.

Clamp covers the time needed to secure the piece in the fixture.

Position means to move the table and fixture at rapid traverse rate until the workpiece is next to the cutter.

Mill represents the time that the cutter is actually at work.

Elements 6, 7, 8, 9, are the reverse of elements 1, 2, 3, 4.

Clean refers to the cleaning of the fixture to prepare it for the next piece.

Other elements may occur in variations of the milling operation like: (1) Gage or measure the workpiece. (2) Rapid traverse between consecutive cuts. Also, elements may be repeated.

It is apparent that output can be increased by eliminating elements and still getting the same results. The only directly useful elements are those which create the desired change in the workpiece. In the case of milling, the productive elements are those occasioned by the cutter acting upon the work. They are called the machining elements.

Machining or processing elements may be decreased in size, but not conceivably eliminated entirely, without doing away with the operation. However, even that is desirable if the results can be accomplished in a more efficient manner, as by performing one cut in conjunction with another.

Evidently, one objective of tool planning is to devise and arrange the physical items of an operation to minimize the number of elements and the time of each essential element. To do this, the procedure is to:

1. Break down the operation into suitable elements.
2. Study each element separately to find most economical disposition for it.
3. Synthesize or put together the tested elements in the most efficient way.
4. Provide the means to carry out the planned operation.

Finding the most economical form of an element

Nonmachining elements are usually performed by people. Where tools and machines are used, and that is most often so in manufacturing, they should be so planned as to enable the human operator to work efficiently. Once the features which do this are built into tooling, they encourage efficiency; but if omitted, additional expense, often a duplicate expenditure, is incurred in establishing them. Much of the reputation of "efficiency engineering" has been earned by improving tooling to the stage where it promotes economical routines. This is a reflection upon tool engineering which should have provided for sound methods in the first place.

The human contribution to doing a job is made up of motions. Good tooling helps the human operator by aiding in economizing motions. Analysis of worker activity, motion study, is a large field in itself, but its principles can be understood and used advantageously by the process and tool engineer. Habel and Kearful[1] listed the principles of motion economy of concern to tool engineering as:

"1. Eliminate all *unnecessary* movements of the workmen.
2. Shorten and simplify all necessary movements.
3. Balance the work.
4. Minimize use of the eyes.
5. Eliminate the use of hands as holding devices."

Motion economy is applicable almost entirely to the noncutting elements of an operation: those performed by human movements. That does not mean that cutting may not occur at the same time as human movements. It is often desirable that it should, but then other principles apply as we shall see. However, in an operation, the shorter the machining time as compared with the nonmachining time, the more important motion economy becomes. The larger the portion of an operation performed by the workman, the more benefit to be derived from a careful scrutiny of his motions.

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[1] O. W. Habel and G. G. Kearful, "Machine Design and Motion Economy," *Mechanical Engineering*, Dec. 1939, Vol. 61, No. 12, p. 897.

Tooling principles which point the way to economy

As has been stated, the principles upon which the use of tools is based point to definite economies. They are:

1. Economy of effort through:
   a. Mechanical advantage.
   b. Transfer of burden and control of power.
   c. Simultation of action.
   d. Transfer of thought.
2. Economy of skill through:
   a. Transfer of skill.
   b. Advantage of perception.

A sufficiently skilled craftsman with only a hammer, chisel, and file or stone can create almost any object or device from metal with the expenditure of enough time and effort. However, a prime purpose of modern manufacturing methods is to minimize time and effort by application of suitable tools. In every case, however, a reduction in the cost of direct labor is attended by an increase in other costs. A fixture may provide the means for employing a lower order of skill for an operation, but time is consumed in fastening the part if the fixture is supplied. A part may be drilled without a jig, but less skill is required and less time is consumed in locating the hole if a jig is furnished. However, if the part is to be moved around during the operation, more effort may be expended because of the added weight of the jig. Principally, though, an increase in cost results from the actual expenditure for the jig. Tools are justified only by the savings they afford over the costs they incur.

The factors that enter into economy of tooling

An important part of planning is to select, specify the features of, and approve the designs of machine tools, auxiliaries, cutting tools, fixtures, jigs, dies, or gages on the basis of the savings they offer. The goal in this respect is to find ways of getting low cost consistent with adequate performance. Many ingenuities have been devised to promote economy. A list of all of them would fill volumes. However, they can be described by the comparatively few principles upon which they are based. These principles fall into the following classes:

1. For economy of direct costs:
   - a. Motion economy.
   - b. Prevention of undue strain and fatigue.
   - c. Alleviation of heavy manual labor.
   - d. Conservation of skill.
   - e. Combination of operations.
2. For economy of indirect costs:
   - f. Reduction of cost of auxiliary services.
   - g. Promotion of safety.
   - h. Co-ordination with movement of materials.
   - i. Consideration of availability.
3. For economy of fixed costs:
   - j. Low construction costs.

ECONOMY OF DIRECT COSTS

Tooling for motion economy

To eliminate unnecessary movements, the following rules are helpful:[2]

1. Replace hand movements by automatic machine movements where practical.

2. Replace hand movements by foot or knee movements.

3. Eliminate the necessity of passing work, tools, and controls from one hand to another.

4. Combine movements by providing controls with multiple functions. Also combine two or more tools into one, wherever possible.

5. Use mechanical ejectors.

6. Arrange so that finished work will drop from fixture into discharge chutes. Use drop discharge chutes and the push through idea.

7. Aid locating by means of slides, guides, flanges, stops, bell-mouthed holes, and bullet-nosed pins, etc.

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[2] Based on *Motion Economy Rules to Guide Process and Tool Engineer*, Saginaw Steering Gear Division of General Motors Corporation.

Fig. 17. An automatic-lathe operation. One workman operates two automatic stub lathes that rough the outside diameter and two faces of the port housings of roller pumps. Carbide tools with a spindle speed of 498 r.p.m. provide a cutting cycle of only a few seconds, but during that time the operator is fully released to attend to the alternate machines. One operator finished 130 pieces per hour.

A quick operation like this one might be hazardous, but to prevent possible injury, both machines have been equipped with attachments that make it necessary for the operator to use both hands concurrently at remote control stations to start the automatic machining cycle. (Courtesy Sundstrand Machine Tool Co., Rockford, Ill.)

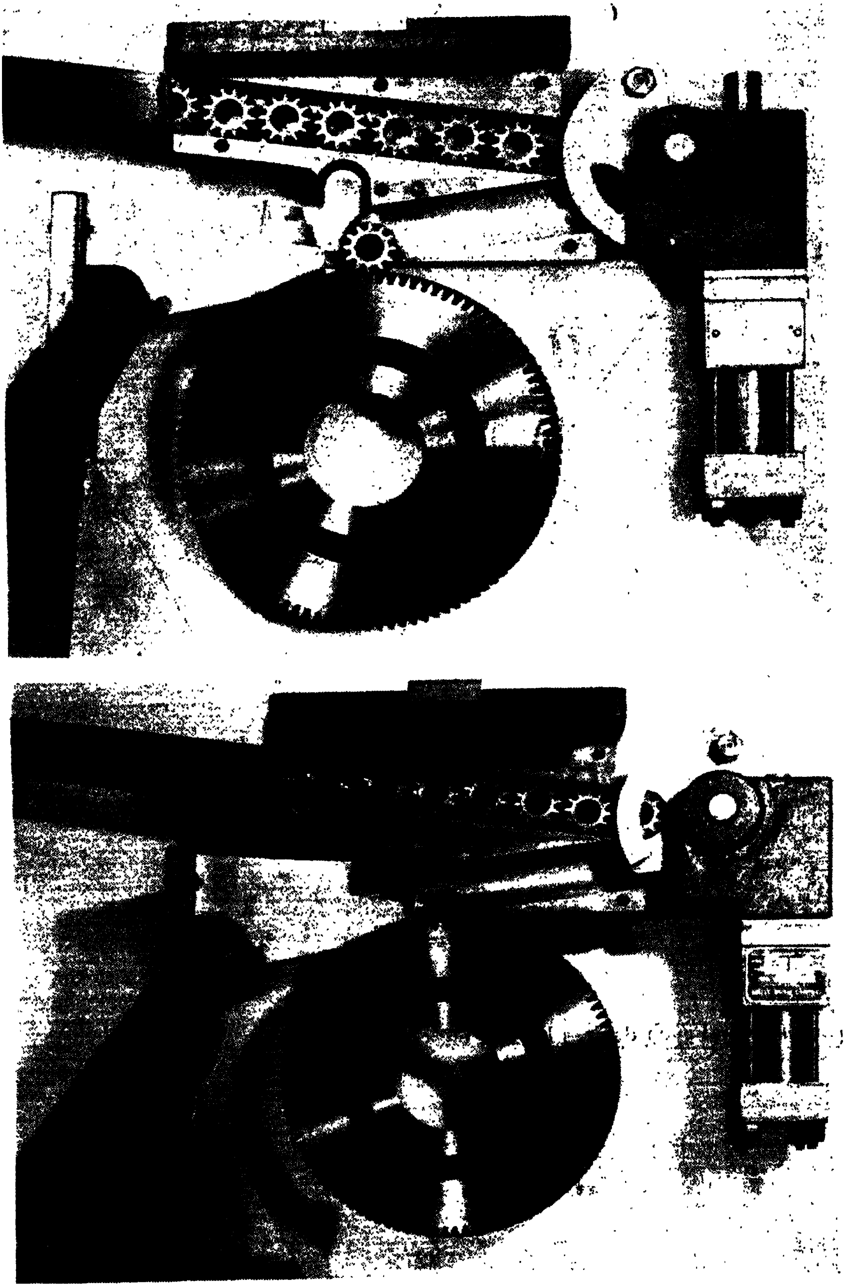
8. Preposition tools.

9. Provide for fast feed of tools or carriage up to work and fast return to unloading point.

Fig. 18 (opposite page). A gravity-chute feed for a rotary shaver. Three hundred pinions per hour are produced on this type of machine.

At the top the loading cycle is shown. Gears placed in the chute roll down to the shuttle rotor that carries one at a time to the chute below. The finger above the shaving cutter stops each gear as it rolls into position. An arbor is automatically pressed into the gear and holds it in position during the shaving cycle.

At the bottom the events completing the operation are shown. The arbor is withdrawn from the gear, the shaving cutter turns slightly, and the finished gear is discharged down a chute. In the meantime the shuttle rotor has picked up another gear, which it will carry to the lower chute to start another cycle. (Courtesy Michigan Tool Co., Detroit, Mich.)



[Fig. 18]

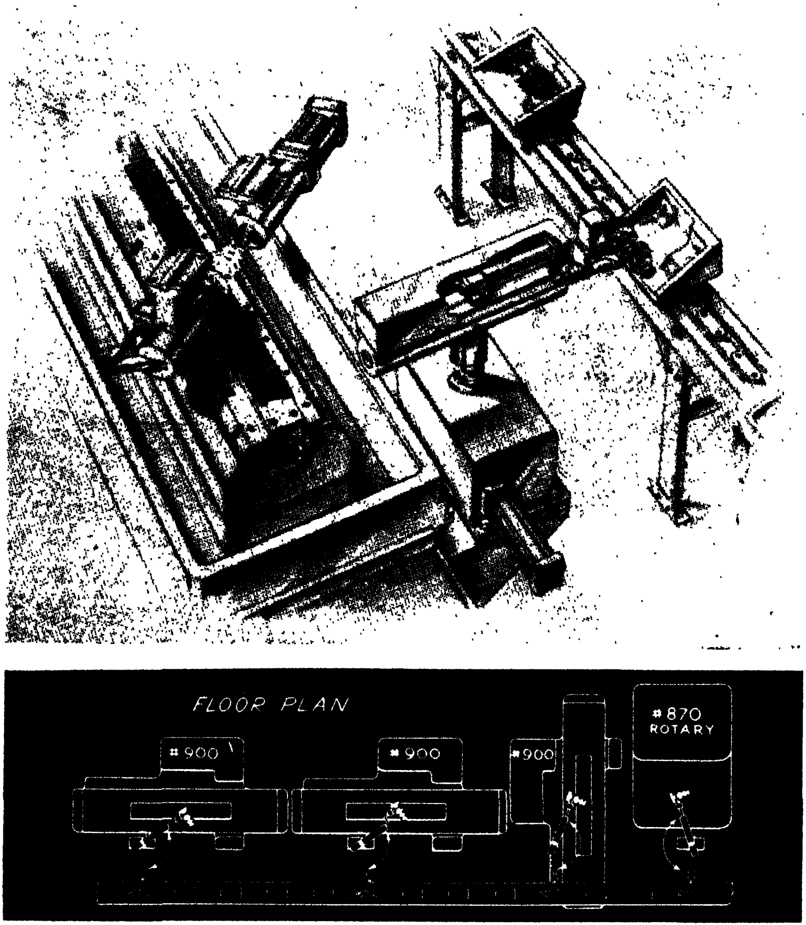


Fig. 19. Another example of automatic loading. The upper sketch shows a loading arrangement to carry a cluster gear from a conveyor to a rack-shaving machine and to return the gear after it has been finished. The lower diagram shows several such devices loading clusters on successive machines for finishing the several gears on each cluster.

The loading arm has fingers that grasp the gear on the conveyor. The gear is picked off its conveyor rest, and the arm turns and carries the gear to a position between the centers of the machine. The machine centers move together to hold the gear, lifting it off the lower fingers. The machine then goes through the shaving cycle, the centers retract, and the loader returns the gear to the conveyor and releases it. (Courtesy Michigan Tool Co., Detroit.)

The first rule points out the application of the principle of transfer of thought or human attention to machinery. For instance, a turret lathe operator performs motions in indexing the turret, bringing the tools to position, changing speeds, and engaging the feed. He may even be unoccupied during part of the cycle. Where the amount of production is sufficient to justify the additional tooling cost, the job can economically be put on a semi-automatic lathe where the operator is released from all routine duties except for placing rough pieces in the machine and taking out the finished ones. This may enable him to operate two machines, as indicated in Fig. 17. In some cases fully automatic machines may be used, where the stock is fed into place without constant attention from an operator.

Gear shaving is an example of an operation for which the cutting time is very short, a matter of 10 sec for an average gear, and where considerable benefit has been derived from the use of automatic loading devices to eliminate human motions for high production. Fig. 18 shows a loading device for a rotary shaver. The gears are placed in a chute from which they are carried one at a time to the loading position. An arbor automatically engages each gear as it comes to the cutter and holds it during the cutting cycle. Then the arbor is withdrawn, and the gear is ejected down a chute. Fig. 19 shows a different type of loading device which picks gear clusters off a conveyer and swings them into positions on successive machines so that the several gears on each cluster may be shaved. On each machine, a cluster is held between retractable centers while being finished.

Substitution of machine action for hand movements need not always be extensive to be worth-while. A simple, but worthy, arrangement is that of Fig. 20, where a chain is attached between a control valve lever and the machine to bring about clamping and unclamping, as the table is moved to and from the loading position. In Fig. 156 the spring-loaded pressure and bushing plates hold the parts in place when the head descends. The operator does not need to do any clamping.

A similar arrangement that has been used at the Saginaw Steering Gear plant is that of closing a fixture by movement of a cam clamp handle against the machine frame. In power-milling operations a typical cycle includes loading, clamping the fixture by hand, and starting the machine. The equipment can be arranged so that it will only be necessary for the operator to place a part in the fixture and start the machine. The clamping can be done by having the fixture clamp handle ride as a cam against some part of the machine frame to tighten the clamp.

As another example, the indexing base for the fixture of Fig. 231 is indexed automatically upon return of the table to its starting position.

The replacement of a hand movement by a foot movement is commonly done on punch presses which are tripped by a foot pedal. There are many opportunities for using foot pedals on all types of

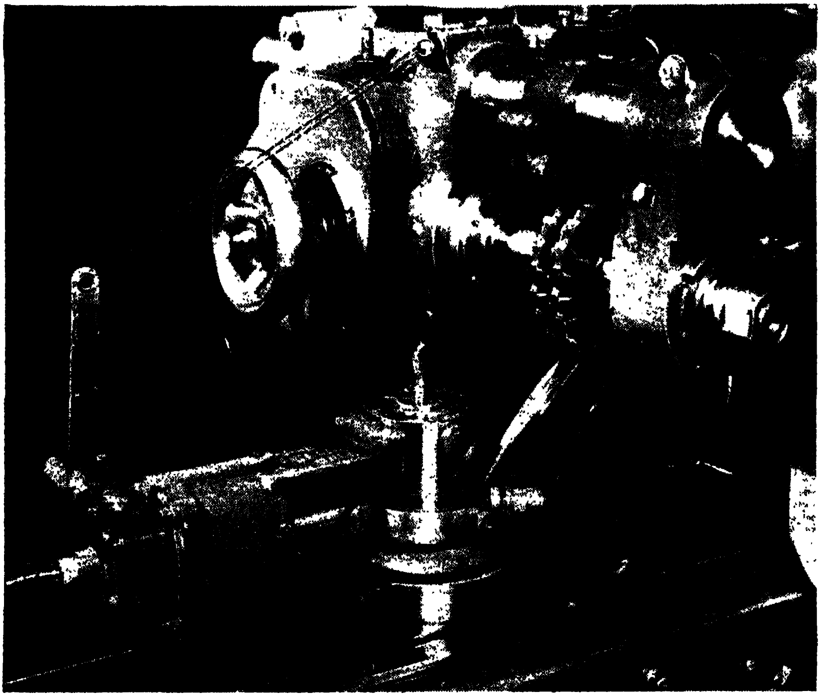


Fig. 20. An air-operated collet-holding fixture. The use of an air cylinder reduces operator effort. The valve handle is connected to the machine by means of a chain so that the valve is automatically opened, when the fixture on the table is traversed away from the cutter.

This is an example of a versatile commercial device accommodating a wide range of collets for general utility. (Courtesy Zagar Tool, Inc., Cleveland.)

machines or fixtures. A press on which the tapping head is lowered and raised by a foot treadle is referred to in Fig. 31. In the setup of Fig. 32, a foot-operated valve is used to control the flow of air to blow the chips away. Even as conventional a holding means as an ordinary bench vise can be improved to save motions by an arrangement for foot operation for repetitive operations (shown in Fig. 21). The vise is opened when the foot pedal is depressed to the shock-absorbing stop on the floor. When the pedal is released, strong springs activate the toggle to clamp the jaws. This type of vise has been used for many operations at the Cadillac Motor plant. For greater gripping power, air or hydraulic cylinders may be used, connected to foot-operated valves. Foot movements can be done at the same time as hand movements.

A control with a dual function to save hand motions is shown in Fig. 22. There, the lever which clamps the work-holding jaws is interconnected with the tripping mechanism of the punch press. As soon as the jaws lock the work in position, the press is tripped and the tool is forced downward. Combined clamping is another means of observing this rule. In Fig. 231 one vertical clamp serves to secure two pieces at each end of the fixture. Common examples of two tools combined into one are double-end wrenches, combination tack hammer and puller, and combined pliers and wire cutter. A dual-purpose cutting tool is the step drill, used for production in quantities of holes which must be drilled and counterdrilled or drilled and countersunk. An illustration of step drills and the work done by them is given in Fig. 23. The punch and broach of Fig. 22 is a combined tool.

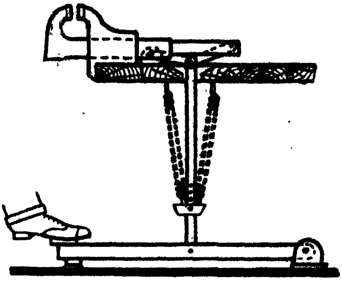


Fig. 21. A foot-operated bench vise. (Reproduced by permission from Barnes, *Motion and Time Study*, 3rd ed., John Wiley & Sons, 1949.)

Items 5, 6, and 7 above are incorporated, with other principles, in the setup of Fig. 24. The pieces are ejected on to the small chute attached to the punch holder, from where they drop on to the large chute on the right side of the press. The operator is placing two pieces at a time on the die and is aided by the ample rounding of the ends of the plugs.

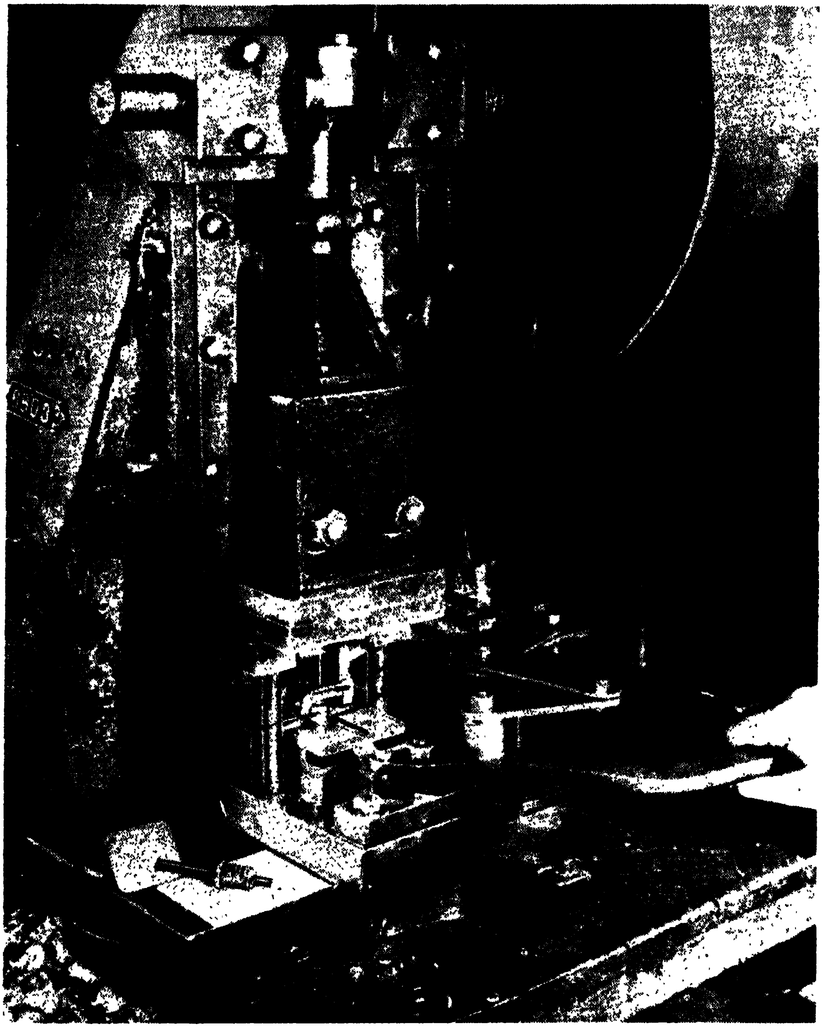


Fig. 22. A fixture for a combined piercing and broaching operation on a lock cylinder. The jaws holding the work are clamped by the lever at the right, and it is interconnected with the tripping mechanism of the punch press, so that as soon as the jaws are locked, the press is tripped and the tool is forced downward. The tool is a combined punch and broach. Its end pierces holes, and the broaching teeth on its sides follow through and size the holes accurately. So well adapted is this fixture that nine hundred pieces are pierced and broached in an hour. (Courtesy New Jersey Zinc Co., New York.)

An inclined press, like that shown in Fig. 25, is a common resort to arrange for work to pass through for discharge. In this setup the V-guides on the simple loading tray direct the pieces into the loading chute and save motions that might otherwise be necessary for this purpose.

The work is pushed through the die, shown in Fig. 26, by the loading movement of the operator.

Careful motion study reveals that to find the exact place where an object must go consumes a finite amount of time, small as it may be, and involves a distinct motion or set of motions. These can be eliminated or mitigated by providing means to help an object slip naturally into its right position. Slides, guides, flanges, stops, bell-

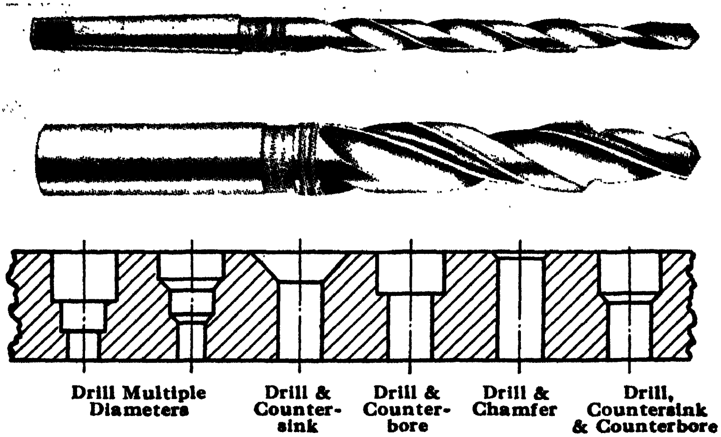


Fig. 23. Step drills. Step drills are used to drill holes of two or more diameters in a single operation. Such drills are also used to drill a hole and then burr it, countersink, or counterbore it at the same time.

There are two general types of step drills—the regular or conventional type and the subland type. The regular type, shown in the top view, is constructed like a regular drill, with the same margin continuing through the various diameters. To produce a sharp corner, it is necessary to undercut the margin. After the point has been sharpened back to this undercut, the drill must be entirely reworked or discarded.

On the subland type, shown in the middle view, the margins of each step are separate, and the drill can be used up entirely without loss. Thus, while the subland type has a higher initial cost, its net cost per hole is considerably lower where there are a large number of holes to be drilled with it.

Typical holes formed by step drills are shown in the bottom view. (Courtesy Chicago Latrobe Twist Drill Works, Chicago.)

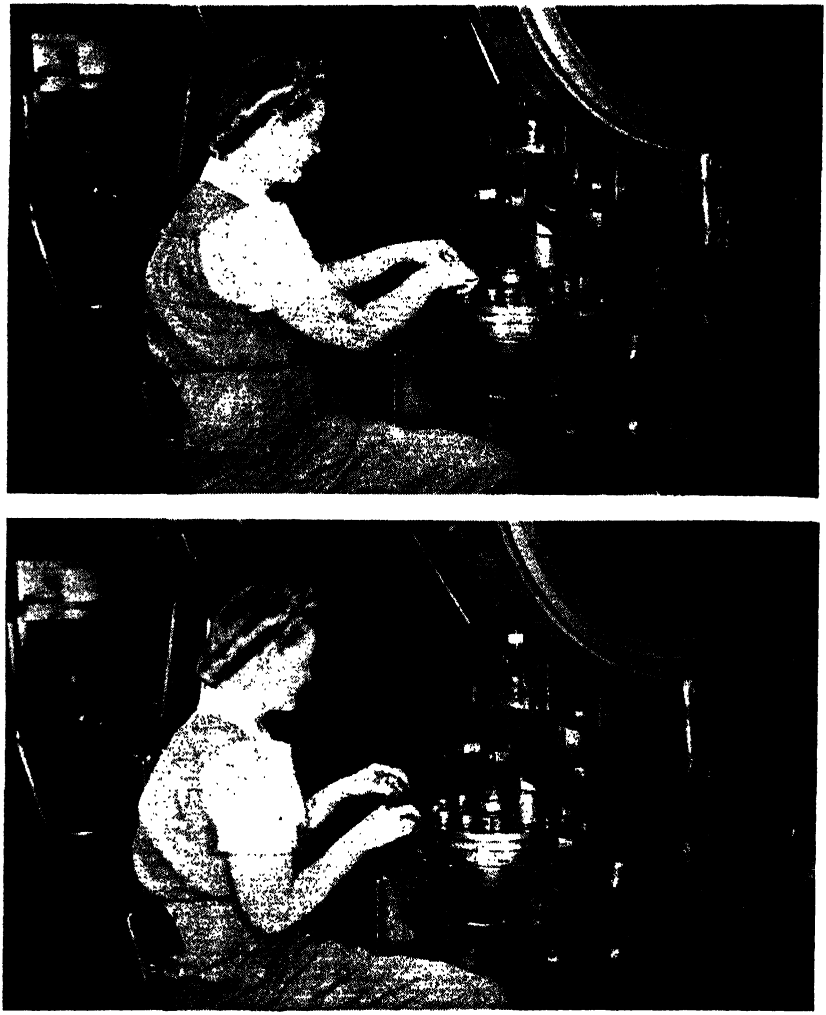


Fig. 24. A die setup designed to utilize full worker capacity. As the press strikes, the operator places two pieces on the die in the indexing die block. Her hands are well outside the danger zone as shown in the upper picture. Finished pieces are ejected automatically onto the chute. During the upstroke of the press the operator picks up two more pieces, as shown in the lower photo, in preparation for loading. (Courtesy Federal Metal Products Co., St. Louis.)

mouthed holes, bullet-nosed pins, etc. are among the means used to help direct objects into proper alignment. Attention has just been called to adaptations of this principle in Figs. 24 and 25. Another example is given by the large chamfer on the locator of Fig. 198.

The fixture of Fig. 27, mounted on a slide and brought against stops at the ends of its travel, serves to position the work easily with the tools. The two holes in the parts of Fig. 48 are positioned in line with the drill spindle and then with the tap spindle by the linkage built into the fixture.

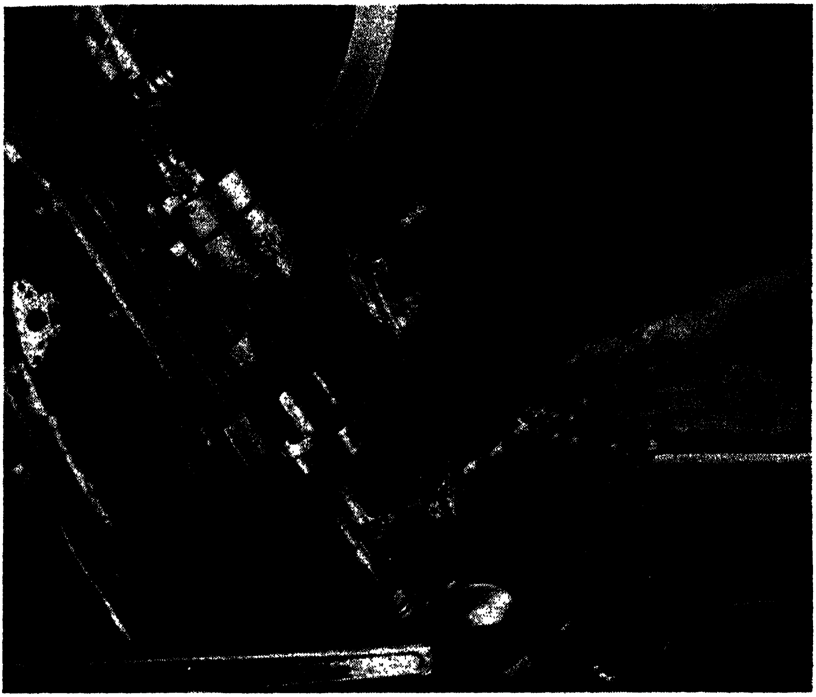


Fig. 25. A chute feed on a press. Output on this inclined press was boosted from 1400 to 2800 pieces per hour following installation of the self-loading tray that practically reduces the loading effort to finger movements aided by guides to preposition the pieces. The work passes through the die and falls out in back of the press. The scrap is pushed through below the die. (Courtesy Penn Electric Switch Co., Goshen, Ind.)

When a piece with a hole in it is placed on a plug, or a plug is inserted in a hole, the two will tend to jam or bind if the fit is close

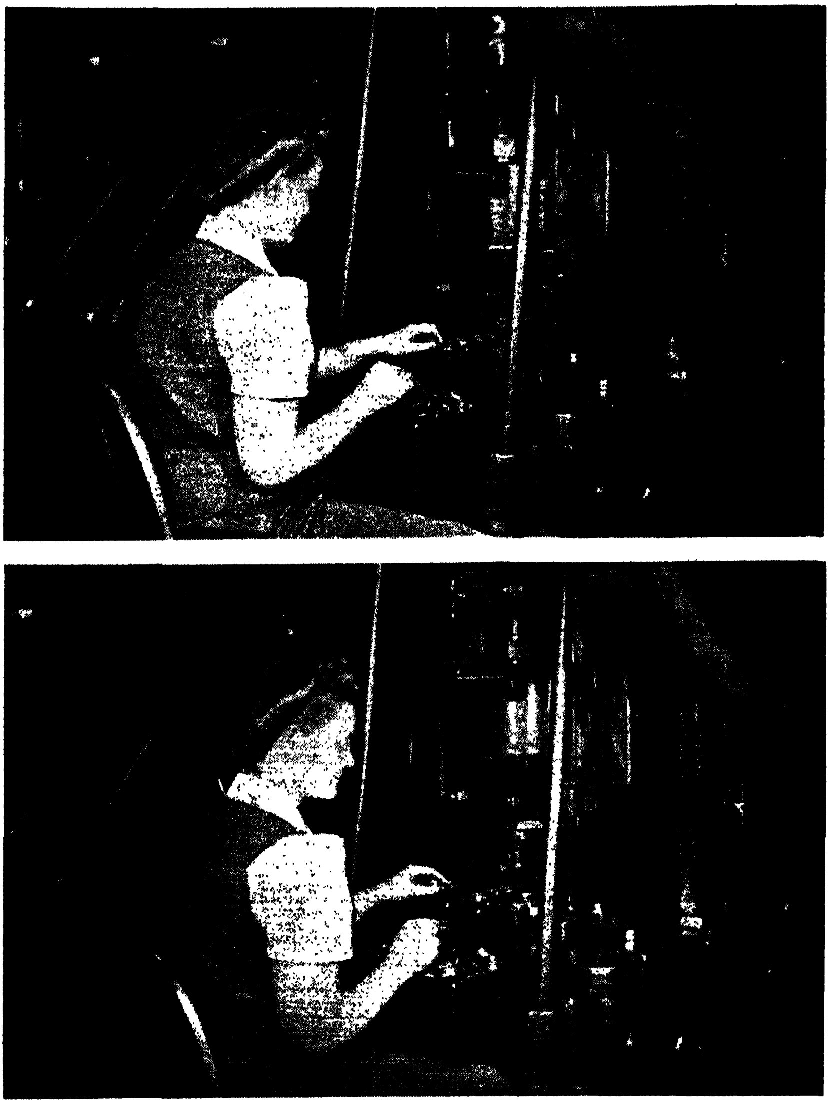


Fig. 26. A punch press setup in which the work is pushed through the die on each stroke. Work is inserted with both hands outside the danger zone of the die. For each complete cycle of either hand two pieces are formed since the stock is inserted alternately by the hands. (Courtesy Federal Metal Products Co., St. Louis.)

and if they are not started straight. Extra motions and time are then consumed in realigning the pieces. This situation may be alleviated by modifying the members in the ways indicated in Fig. 28.

Prepositioning a tool to bring it into proper position for use often involves a set of motions during each cycle of an operation. These can be totally or partially eliminated by an arrangement to hold the

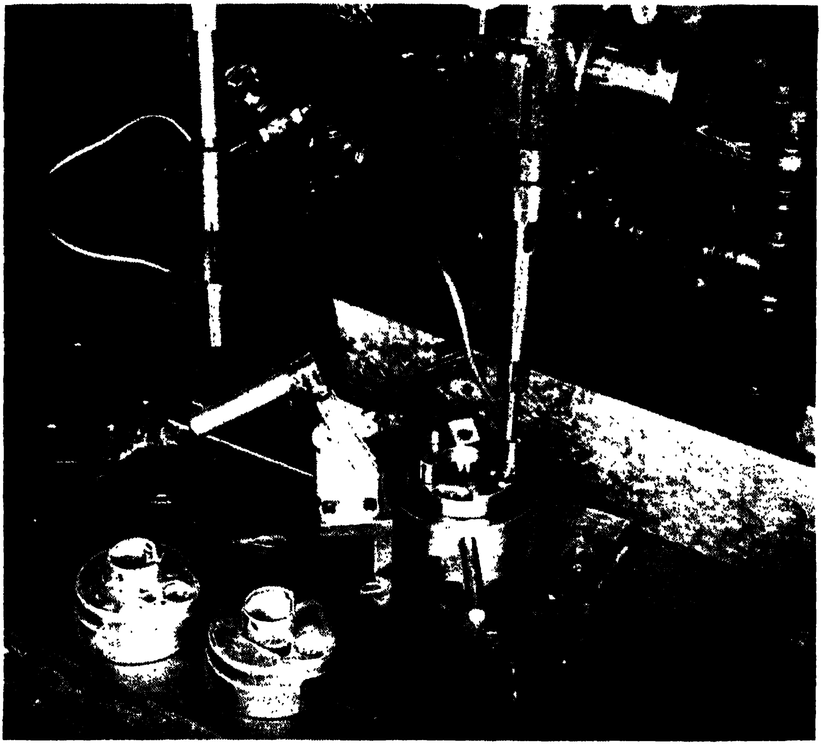


Fig. 27. A reaming fixture. This fixture for reaming two holes in the aluminum die casting shown is a simple type in which the casting is held by a toggle clamp fastened to an angle bracket. Toggle clamps like these can be purchased in many standard shapes and sizes. A single movement of the lever brings the clamping pad to bear on the workpiece, holding the piece on the locating block. The entire fixture slides on a track clamped to the table of the two-spindle drill press. In the position shown the fixture is at the right end of the slide against a stop where it is aligned with the reamer in one of the drill-press spindles. The reamer is piloted in a hole in the block to insure a true hole. After one hole is reamed, the block with the casting still in place is slid to the left under a second reamer that acts in the same way. A ring ejector is used to lift the casting off the fixture, on which it is a snug fit. (Courtesy New Jersey Zinc Co., New York.)

tool in a predetermined place so that when needed it may be grasped in the position it will be used. For this purpose a holder is provided to which the tool is returned after it is used. An example of prepositioning and an accurate evaluation of the benefit from it is shown in Fig. 29 from a study by Barnes and Mundel. The job studied consisted of driving several 8–32 screws down ½ in. until tight. The operation was performed with a ratchet screwdriver, from three different positions; fully prepositioned as indicated at *A*, partially

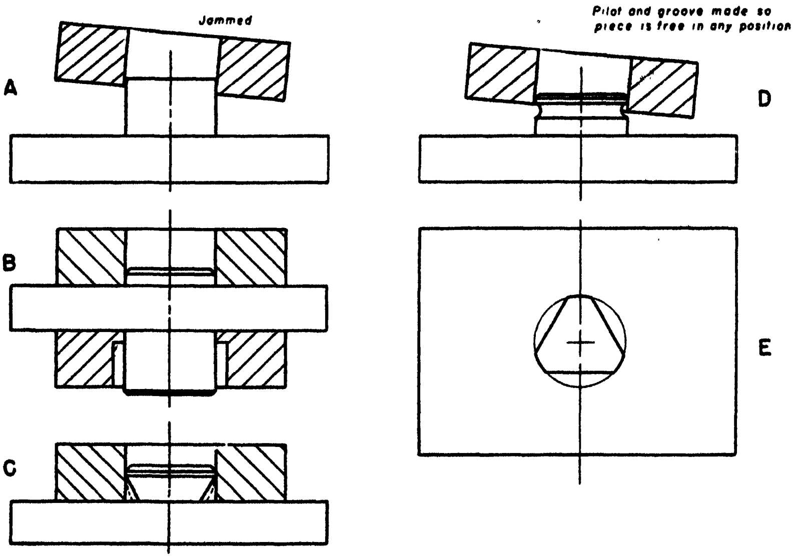


Fig. 28. Ways of eliminating binding or jamming. A close fitting hole and plug can easily become jammed, as shown in view *A*. Then extra movements and time are necessary to align them so they will slide together. The larger the clearance between the hole and plug, the less chance of jamming. Where a close fit is necessary, the means shown in views *B*, *C*, *D*, and *E* are helpful to eliminate binding.

View B depicts a short length of plug-to-hole contact, so that binding does not take place before the two are fully in place.

View C shows a plug with tapered sides leaving only a short band for contact. The plug may also have a spherical form.

View D shows an aligning shoulder created by a small groove near the end of the plug. The relief gives clearance to the edge of the hole so it does not bind. After the hole has passed over the groove and its shoulder, there is sufficient stability to prevent jamming.

As in *View E*, the plug may be cut away to leave three zones of contact.

prepositioned like at *B*, and not prepositioned at all. The time for the operation with the prepositioned tool was taken at 100 per cent; the time with the partially prepositioned tool was found to be 23 per cent more; and the third arrangement 46 per cent more than the first.

Sometimes hand tools may be prepositioned by being mounted permanently. An example is a small power wrench mounted under a work bench, with the chuck protruding just above the top, for an operation of assembling screws into a small part. The screws are placed in the chuck and the part is brought down to the chuck as it turns the screw into the piece.

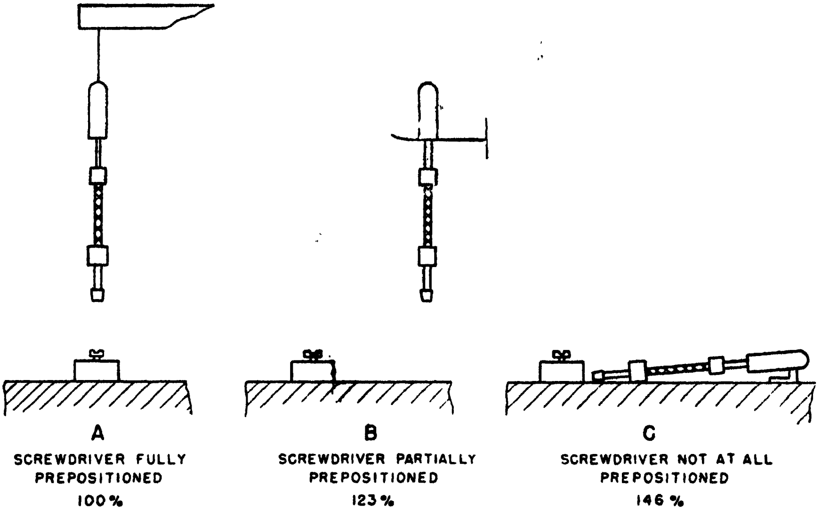


Fig. 29. A concrete example of savings to be derived from tool prepositioning. The percentages show the relative time between the instant the screwdriver is grasped and the instant it is released after running down an 8–32 screw. Thus, if the time to do the job with the fully prepositioned screwdriver is 100 per cent, the time required for the partially prepositioned screwdriver is 23 per cent more, and without prepositioning is 46 per cent more. (Adapted from Barnes and Mundel, "A Study of Hand Motions Used in Small Assembly Work," *University of Iowa Studies in Engineering, Bulletin 16*, 1939.)

The principle of prepositioning is carried out by putting springs under strap clamps on fixtures. The clamps of Fig. 65 are arranged in that manner. The straps slide into place over the work, and the operator does not have to hold them while inserting the work.

There is usually a period of machine action in an operation during which no useful work is done. That occurs while the work is being brought to the cutter, or vice versa. It may or may not correspond to a period of idleness on the part of the operator, but it does represent a definite period of time in the progress of the operation. As indicated by the foregoing rule number 9, it is desirable to provide for a rapid rate of feed or traverse during this interval to shorten it as much as possible. This is an accepted feature of most power-fed machine tools, and it is pointed out as part of the arrangement of Fig. 46. The drill head units of Fig. 67 have a built-in cam feed giving rapid approach and return in the feed cycle.

Sometimes there are spaces between surfaces being cut on a piece or periods in which the cut is comparatively light. In those spaces a high rate of feed is desirable to save time. Such an arrangement is presented in Fig. 231.

To shorten and simplify necessary movements, the following apply:[3]

10. Make necessary movements as short as possible without crowding the operator. Provide for a small work space and keep movements within the workspace.

11. Arrange for getting new work from tray, hopper, or chute as close as possible to loading point or from location close to discharge point so as to overlap movements.

12. When drop discharge cannot be used, arrange for disposal as readily as possible, in front of the operator or over the front of the machine.

13. When possible keep hand movements within radius of forearm pivoted from elbow. In all events keep within radius of full arm without body bend or twist and without necessity for stepping to reach point desired.

14. Eliminate barriers so that movements can follow shortest path.

15. Cluster and centralize all control levers and starting buttons within the normal working area.

16. Make controls "quick-acting" for high production. For this use toggles or cams instead of screw clamps.

17. Design machines for loading so that loose tools such as pliers, tongs, etc. do not have to be used to place the parts in or remove them from the fixture. Also, avoid the necessity of handling any loose details of jigs, fixtures, gages, etc.

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[3] Based on *Motion Economy Rules to Guide Process and Tool Engineers*, Saginaw Steering Gear Division of General Motors Corporation.

18. If loose tools must be used, mount them in definite location and, if possible, in position to require as little handling as can be arranged.

19. Design machines and tools as much as possible to shed oil and dirt by eliminating flat surfaces.

20. Make locating surfaces as readily cleanable as possible consistent with durability.

21. Provide sufficient room for chips and trimmings and make these places easily accessible for cleanout.

22. Provide compound lines large enough to wash chips and turnings off fixtures, or position air lines to blow off chips. This is to relieve the operator from having to brush them away.

23. If cutting fluid cannot be flowed on work, provide mechanical means for brushing it on.

Figures 24, 25, and 26 show setups in which the loading function can be performed by short movements. In Fig. 25 the pieces are pushed from the tray to chute by finger movements. If the pieces were placed individually in the chute from a box, as is commonly done, hand or arm movements of greater length would be required. In Figs. 24 and 26 the work is loaded from boxes directly in front of the loading stations.

The nature of the operation shown in Fig. 30 is not suitable for loading from directly in front of the die, nor for ejection and drop discharge. In this case rules 11, 12, 13, and 14 are followed. The rough pieces are set on a tray at convenient height to left of operator. A bin on his right is for the finished pieces. The side of the disposal bin is cut down so as not to be a barrier. Movements to these areas next to the die and gage are within recognized limits.

Figure 47 shows an air-cleaning fixture, auxiliary to a tapping operation. It is evident that the operator can place the parts on this fixture by swinging the forearm from the elbow.

The machines of Figs. 68A and 142 conform to the rule of centralizing control buttons by having a box containing starting buttons within the normal working area.

For clamping a few pieces, the cost of a quick-acting mechanism

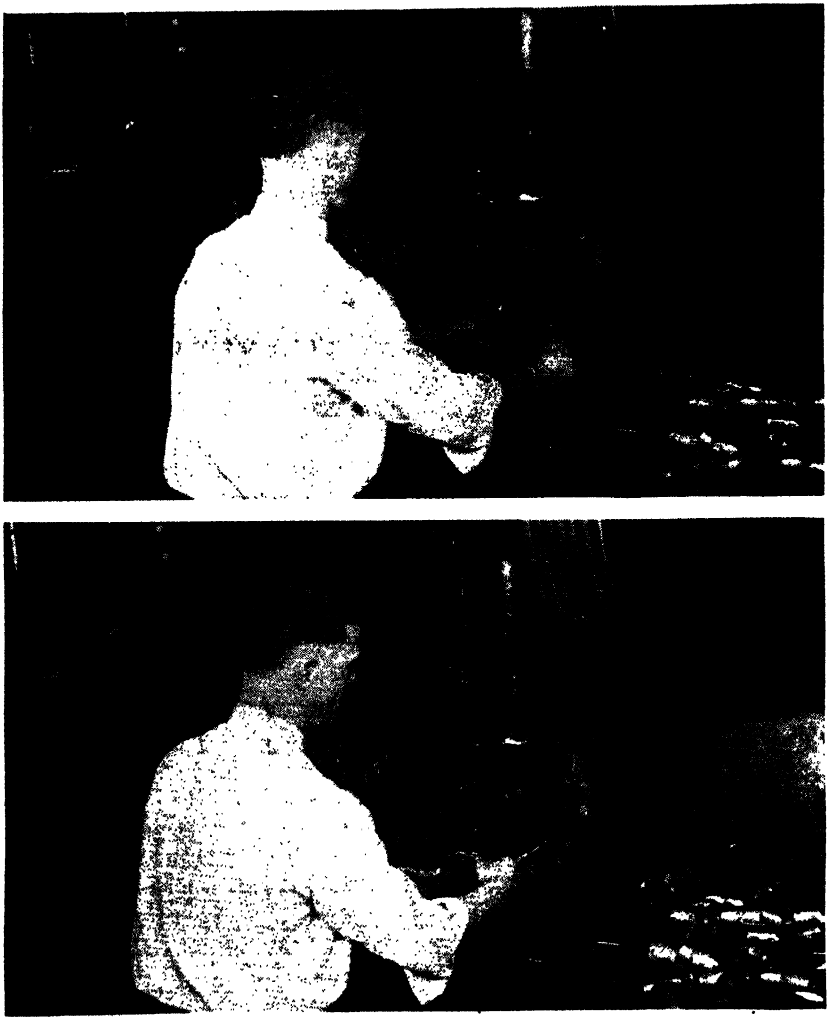

Fig. 30. A punch press setup for convenience and motion economy. When the press is on top of stroke, as in upper photo, the hands of the operator are changing the pieces from one horn die to another. When the press is on the down stroke, as shown in lower photo, the operator places the piece on an inspection gage, conveniently located for that purpose. (Courtesy Federal Metal Products Co., St. Louis.)

may not be justified and screw clamps are commonly used under those circumstances although they are slower. However, for high production "quick-acting" clamps are usually worth-while. They may be hand-operated toggles or cams for most cases, but supplemented by air or hydraulic means when heavy pressures are required. An application of a common type of commercial toggle clamp is shown in Fig. 27. The standard universal jigs of Figs. 43 and 44 clamp the work under the head, which is brought down by one movement of the operating lever. Figures 22 and 65 also show quick-acting clamping.

A further consideration is that there are times when no clamp at all is needed for an operation. It may be possible to slip a part into such a position that it cannot move under the cutting action, and a clamp would be superfluous in such a case. This situation arises most often in drilling and allied operations. Figures 31 and 48 show two operations in which the workpieces are adequately restrained by the locators themselves.

The ring ejector on the fixture of Fig. 27 obviates the need of a separate pry bar to loosen the piece from the locating plug. This conforms to the rule of designing to make loose tools unnecessary. The operator in Fig. 30 keeps a screwdriver in his hand to loosen parts from the horns. An ejector built into the die would serve the same purpose with fewer motions.

Clamps which must have considerable motion to clear the work should have a quick-action when free and a slow-motion with greater leverage when in contact with the work. One such device is the toggle clamp. Others include the bayonet screw, slotted screw, and cam lock.

Among the faults of the setup shown in Fig. 210A is the clamping arrangement whereby two rods passing through holes in the casting are held down in front and back by strap clamps. Each time a piece is taken off and another put on these loose pieces must be handled, which adds considerably to the inefficiency of the setup.

Although loose tools are undesirable, at times their use cannot very well be avoided. Loose tools placed haphazardly bring about pauses in an otherwise smooth routine until they are spotted when needed. This may be helped by providing a definite and convenient position for such tools. A rack may be the solution in some cases.

In Fig. 68B the wrench for the fixtures is loosely held in a bracket in position for use.

If it is necessary to use a wrench on the clamps of a fixture, all the nuts should be of one size so that only one size of wrench need be used.

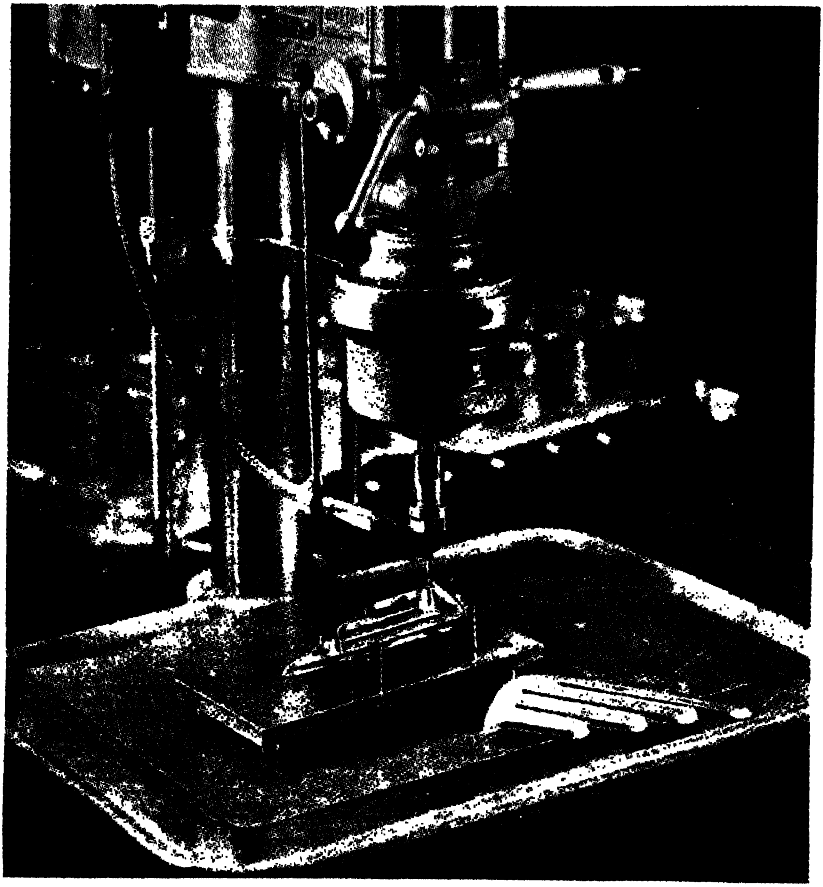

Fig. 31. A fixture for tapping two holes in six hundred and fifty die castings per hour. The irregularly shaped die casting is supported on several pins that hold it level and prevent turning. The plate in turn rests on four pins for legs. The pins raise the fixture off the drill table and the work off the plate and reduce chances of tilting or mislocation from chips. The tap is lowered by a treadle so that the operator has both hands free to load, shift, and unload the work rapidly. A brush connected to a reservoir of oil, with drip feed, keeps the tap lubricated. (Courtesy New Jersey Zinc Co., New York.)

Cleanliness is necessary for accuracy. Dirt always creates a displacement between objects, which results in error. Along with that consideration must go the one of the cost of keeping surfaces clean where harm may result from the presence of undesirable accumulations. Figures 46 and 68A show fixtures in which descending surfaces and ample spaces promote the passage of cutting fluids and chips. A clear passage is provided in the machine of Fig. 53 for the chips to be washed into a compartment in the base, where they can be readily cleaned out. A pan is placed in position in Fig. 231 to collect the chips so that they can be removed conveniently in bulk.

Small locating areas are easier to keep clean. The supporting plate for the casting shown in Fig. 31 rests on buttons and carries

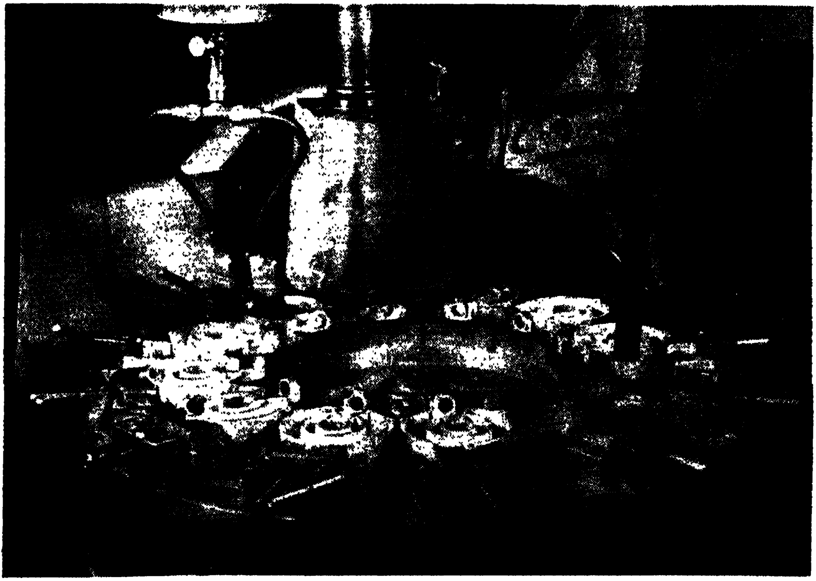

Fig. 32. Rapid face milling of die castings on a light fixture of the dial type. There are twelve stations on the dial that rotates slowly, advancing the work under a twelve-teeth-end mill. A quick-acting clamping holder grips the work at each station. The operator removes two castings and loads two others at stations well away from the cutter, at the rate of six hundred castings an hour. Useful auxiliaries include a sight feed arranged to supply coolant through a pair of paint brushes just before each casting reaches the cutter, and an air hose placed to blow chips off the stations as they are unloaded. The valve for air flow is operated by a treadle so that the operator's hands remain free to load and unload the castings. (Courtesy New Jersey Zinc Co., New York.)

the piece on pins to reduce chances of chips collecting on undesirable areas and accordingly reduce the number of movements necessary to clean away such chips.

Where coolant may not be used or may be supplied only in small amounts, insufficient for washing away chips, compressed-air discharges can be used to blow away chips to clean surfaces. Such an arrangement is shown in Fig. 32 where the air jet is turned on by the operator through a foot pedal when the empty stations are in the correct position for cleaning.

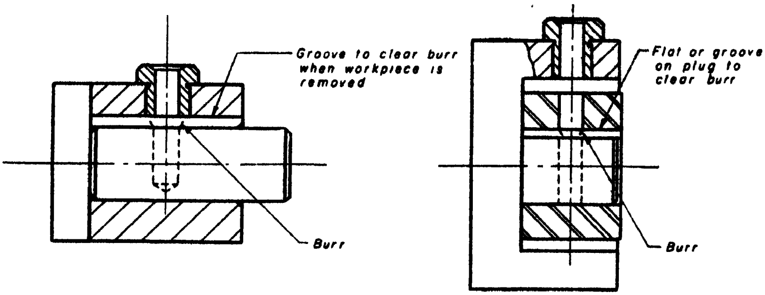
Groove to clear burr when workpiece is removed
Burr
Flat or groove on plug to clear burr
Burr

Fig. 33. Providing clearance for burrs. To facilitate removal of the workpieces on the two jigs, clearance is provided.

Along with chips is the consideration of burrs which are often thrown up from machined surfaces. If clearance is not provided for them, they may make it difficult to remove the workpiece from its locator. Two examples of this are illustrated in Fig. 33. In one jig sketched, the workpiece fits inside a hole in which a groove is made to allow for egress of the burr. The workpiece is located on a plug in the other view. There clearance for the burr is provided by a flat or groove on the plug.

Figures 31 and 32 show operations in which the cutting fluid in small amounts is fed through brushes supplied automatically and supported in position.

To balance the work the following apply:[4]

24. Avoid idleness of one hand.
25. Keep both hands busy with useful work.
26. Provide double station fixtures.

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[4] Partly based on *Motion Economy Rules to Guide Process and Tool Engineers*, Saginaw Steering Gear Division of General Motors Corporation.

For loading, double station fixtures like that shown in Fig. 24 which can be kept supplied by continuous rhythmic motions of both hands in unison are ideal. But where duplicate equipment is not justified one solution is to keep the hands working alternately, like in Fig. 26. In the setup of Fig. 30 both hands are occupied in changing the pieces on the double-horn die while the press is idle. While the press is active, the hands are kept busy performing the inspection operation. The revolving fixture of Fig. 32 has sufficient stations so that two holders may be unloaded and loaded at the same time. Clamp handles are accessible and quick-acting. Foot-operated air control for blowing off chips and automatic coating of the work with lubricant leave the operator's hands free for continuous loading.

To minimize use of the eyes, the following apply:

27. Eliminate hard to find controls (like small buttons).

28. Aid positioning of work by means of slides, guides, flanges, stops, bell-mouthed holes, and bullet pins, etc. Preposition tools.

29. Keep necessary eye use within small space (about within a 6-in. circle, if possible).

30. Provide definite location for loose tools.

Eye movements take definite amounts of time, the same as movements of any other part of the body. Furthermore, the eyes do not see while they move and need a small interval of time for fixation upon an object when they do stop. For small objects or difficult situations, the natural tendency is to direct finger or arm movements through the eyes. An increment of time is lost in eye-directed movements. Consequently, it is desirable to arrange to make the use of the eyes unnecessary as much as possible. If the hand and fingers must grope for small buttons or controls, eye direction is almost certain to be brought into play. Large buttons help to obviate this detraction. Large palm size buttons are favored for starting and stopping, as the operator can instinctively make a motion in the general direction of such a button with a good likelihood of contacting some part of it. Aids in locating work and prepositioning tools not only save positioning movements, as previously pointed out, but also reduce the tendency or necessity of eye direction to supplement the positioning motions.

If eye movements are required, their cost is minimized by confining them to a small space. Thus, the horn dies and gage of Fig. 30 must have eye attention, but they are placed as close together as possible.

To eliminate use of hands for holding, consider:

31. Eliminate use of hands for holding machine parts.
32. Eliminate use of hands for holding work.

The hand is a most versatile holding device but inefficient for any particular specialized purpose. For almost any specific purpose a mechanical device can be made to hold a part more securely, rigidly, and accurately than the hand, but no such device has the general adaptability of the hand. During a definite repetitive task of holding a workpiece the hands are better left free for other constructive work or even idle for rest.

For machine starting, feed or clamping levers, detents or cam locks are automatically applied to hold the levers in position after they are engaged so that the hand may release them. This is so common that it is normally expected and scarcely noticed by the user. One notable exception is that of rapid traverse levers on machine tools. If rapid traverse is left engaged too long because of lack of attention, the work may run into the cutter at too rapid a rate with disastrous results. Thus, self-retention is often purposely omitted to make sure the operator stays with the lever and can disengage it quickly.

Fixtures are usually holding as well as locating devices. Either function may be fulfilled in any particular case without the other, and it is well to remember to check to see that both are taken care of wherever required. Close location of the workpiece is not of primary concern in the setup of Fig. 31, but the piece is held adequately in the fixture so that the operator has both hands free to load, shift, and unload the work rapidly.

An essential of clamping devices is that they be self locking so that they will hold a setting without constant attention. Proportions of common clamping devices should satisfy this requirement. Commercial jig and fixture units, like those shown in Figs. 43 and 44, often have locking arrangements so that the operator may remove his hand from the handle after he has engaged it. The nonreversible mechanism, of which there are several variations, is acted upon by the handle and, in turn, transmits the clamping effort to the linkage in the jig body, but cannot be reversed by a "kick-back" from the linkage. On the jigs shown, the nonreversible mechanism is in the small housing to which the handle is attached.

Prevention of undue strain and fatigue

Strain hastens fatigue which slows down workers and brings about lags in production. The effects of undue strain and fatigue are mitigated by:

1. Providing comfortable working conditions.
2. Conforming to physiological traits.

Comfortable working conditions are promoted by the following rules:

a. Avoid necessity for operator to assume uncomfortable position. Most of the work should be at elbow level when seated and 6 in. below elbow level when standing.

b. Provide sufficient space to allow operator to stand up to machine as he should. If seated, provide knee clearance so operator may sit close to working area.

c. Where feasible, arrange so that machine can be operated equally well from standing or sitting position. This can be accomplished by arranging the work at 6 in. below elbow height when standing, then by providing a high "posture chair" so that the operator may sit and work at proper levels. When foot controls are used, duplicate upper and lower pedals may be necessary.

d. Avoid circumstances which make it necessary for the operator to walk from one station to another.

e. Provide means to position workpiece conveniently for the operator.

In the operations of Figs. 24, 26, and 30, the operators work in a sitting position. In these well-planned operations the work is done at or near elbow height. In the operations indicated by Figs. 70 and 142, it is intended that the operator should stand. In these cases, the work is positioned approximately 6 in. below elbow level.

Measurements[5] made of 13,656 male subjects in a standing position without shoes showed an average elbow height of 43 in. above floor level. On the basis of a forearm inclined 15 to 20° plus one inch for heel height, an average workplace height of 38 inches is indicated.

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[5] E. P. Cathcart, E. R. Hughes, and J. G. Chalmers, *The Physique of Man in Industry*. London, England: Industrial Health Research Board, Medical Research Council, No. 71, 1935.

For massiveness and rigidity, it is desirable that grinding machines should have heavy box-like beds. Notice the recess in the front of the base of the standard cylindrical grinder of Fig. 34 to provide foot clearance, permitting the operator to stand close to the working area.

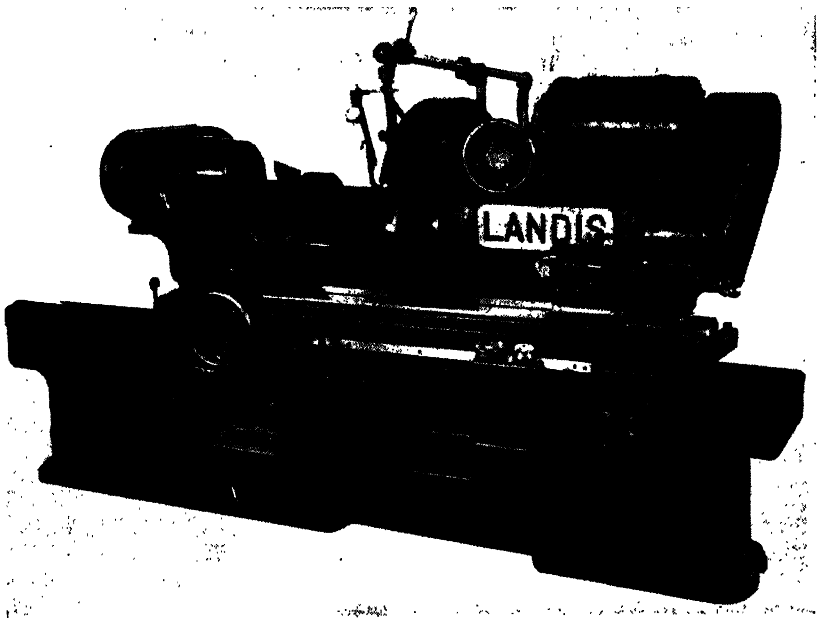

Fig. 34. Front view of a 14 × 48 plain hydraulic grinder. A recess is cast in the boxlike base for toe clearance, so that the operator may stand close to the table for loading and also observe the grinding action. (Courtesy Landis Tool Co., Waynesboro, Pa.)

The drilling units on the machines depicted in Fig. 68A and B are arranged around and outside of the workholding index table. To load the work, the operator would have to reach too far if it were not for the notch made in the bed at the loading station of each machine. The cut-away portion of the bed gives the operator access close to each station of the fixture as it comes into position to be unloaded and loaded.

A disadvantage of a dual milling setup, like that of Fig. 46, is that the operator must move from one end of the table to another to attend to the fixtures. This calls for considerable extra exertion and allows little chance for him to sit. A better arrangement is to mount the fixtures on an indexing base, as shown in Fig. 231, to bring the fixtures successively to the same accessible position to the operator.

Where work must be done in several locations on a unit, means to position it conveniently is usually advantageous in making the operation quicker and keeping the operator from having to take awkward or strained positions. Assembly and welding are two types of operations in which this is often a consideration. Two kinds of welding positioners are shown in Fig. 35. The second is power-operated and, therefore, faster than the first, which must be moved by hand.

To conform to physiological traits, the following rules apply:

f. Build foot pedals so that they may be operated with comfort and by either foot.

g. Where possible levers such as feed handles on drill presses and arbor presses should be made reversible so that they can be operated by either the right or left hand.

h. The operator who is seated can use both feet to operate pedals.

i. Build controls of proper size, shape, and weight, and build to operate without undue effort.

Pedals should be arranged so that the foot rests upon and moves about the heel. When the operator is standing, this allows part of the weight of the body to be carried by both feet. When he is seated, it provides a steadying influence. The typical foot accelerator of an automobile is a good example of this idea. The pedal of Fig. 21 is poor in this respect.

A cushion or spring is desirable to check pedal movement and eliminate shock of bringing it against a solid stop. The cushion under the pedal of Fig. 21 carries out this principle.

Where only one pedal is used, it should be wide enough so that it can be depressed equally well by either foot. A pedal placed across the entire front of a machine permits a wide choice for the positions of the feet.

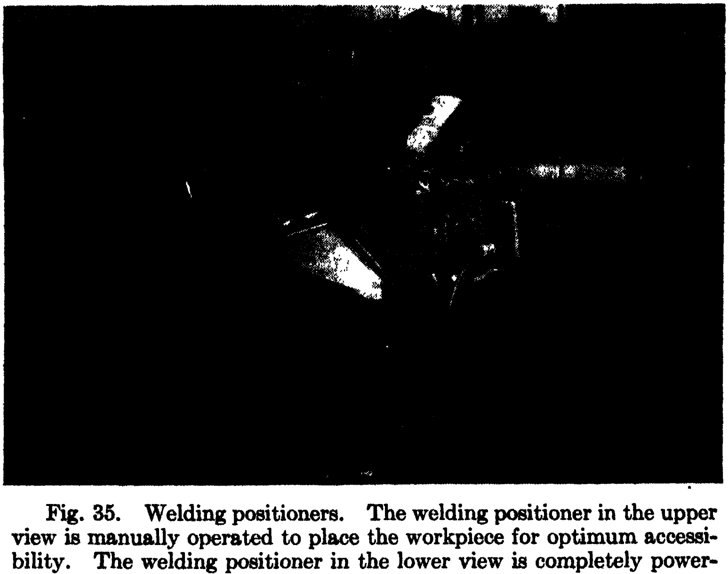

Fig. 35. Welding positioners. The welding positioner in the upper view is manually operated to place the workpiece for optimum accessibility. The welding positioner in the lower view is completely power-operated and is equipped with a variable-speed table-rotation mechanism, which is advantageous in welding circular forms. The power tilt can be run to 135° from the horizontal, and the table rotates 360° regardless of tilt.

Both models have a 1200 lb capacity. (Courtesy Cullen Friestedt Co., Chicago.)

Duplicate controls, pedals, or levers are fitting in three respects. They may be used by an operator to shift routine from time to time, operating the lever for a while with one hand or foot, and then, for a while, with the other. They are equally adaptable to right- and left-handed persons. And duplicate controls make it easier to balance the movements of any type of operation performed on the machine. Thus, if an operation requires that most of the loading and unloading be done by one hand, the other can be used to operate the lever, whichever it may be.

Investigations[6] have shown that handles for tools and cranks presenting the largest bearing area to the hand are most efficient. This means that the least effort is expended in operating them when the unit pressure on the hand is lowest. Generally, straight cylindrical forms have been found more effective than those of varying cross section.

Screws or nuts that must be turned should not be smooth nor even knurled if exposed to oil. An expedient is to insert a pin diametrically through the head of a screw, projecting an inch or more on both sides, to give more leverage. Short pins are uncomfortable, but heavy pins in large screw heads, like those shown in Fig. 231 top and side, are helpful. For small screws, inserted or integral wing blades are convenient. Good leverage combined with comfort can be secured from star-shaped knobs like those in Figs. 70 and 71. Knobs, handles, and clamps should be placed so that there is ample space, usually a minimum of $\frac{5}{8}$ in., between them and adjacent walls or obstructions, for finger clearance.

Levers and controls should be so placed that they can be moved by the operator with the most mechanical advantage and the least change in body position. Studies[6] have shown that the strength of the pull on a lever is greatest when the lever is located about 28 to 42 in. above the floor on which the operator is standing. The pull that can be exerted decreases in both directions as the lever position is changed up or down. The most pull can be exerted on a single lever by pulling upward on it, the next by pushing down on it. Push or pull movements in other directions give around one quarter less force.

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[6] R. M. Barnes, *Motion and Time Study,* New York: John Wiley and Sons, Inc., 1940, pp. 233, 237–242.

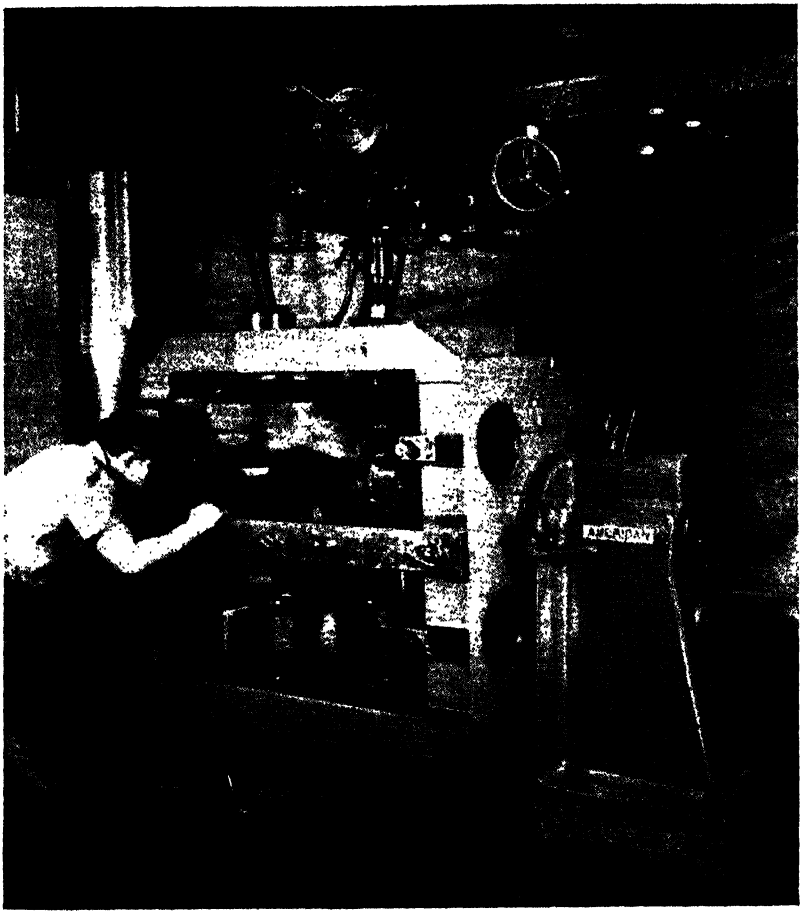

Fig. 36. An example of advantageously positioning a heavy transmission frame for drilling and boring in a jig. The jig is mounted and indexed on a standard indexing trunnion stand carried on the base of a radial drill that drives the cutting tools. Skill is built into the jig that guides the tools, and the work can be done by a relatively unskilled operator.

On the indexing trunnion, the work is brought to a comfortable working height. The operator works at ease; his energy is preserved and his efficiency prolonged. The jig is balanced so it can be swung from one plane to another and located accurately in place by the indexing mechanism. The jig does not have to be shifted, rolled, or lifted, which would require much more operator effort. Because the jig is mounted steadily and is not subject to jolting, it may be made smaller and lighter than otherwise. That means savings in fabrication and storage costs. Chip disposal is also evidently facilitated.

In the case illustrated, the time to machine the piece was reduced from 40 hrs to 8 hrs by the use of the equipment described. (Courtesy American Tool Works Co., Cincinnati.)

Alleviation of heavy manual labor

Heavy labor increases fatigue and narrows the field of suitable labor supply. Its requirements may be decreased by:

1. Transfer of power to relieve manual effort.
2. Lightening of burden.

Transfer of power is found in:

a. Power-driven machine tools,

b. Auxiliaries and devices for moving and lifting heavy work and tools,

c. Air and hydraulic clamping means.

The jig shown in Fig. 36 was mounted on an index base so that it could be moved and positioned easily. Operator effort was reduced considerably and the job made much easier and faster.

In the very early days of their use, machine tools were almost

Fig. 37. A tip-over device for turning engine blocks. This positions the blocks for succeeding operations and reduces operator effort.

Where the conveyors make 90° turns, swivel sections are inserted to save space and reduce the effort of pushing the pieces around the corners. (Courtesy Detroit Diesel Div. General Motors Corp., Detroit.)

entirely hand operated. Later, transmissions were adapted for spindle drives, where the power requirements are heaviest, and then power was applied to feeding. So generally is the principle of transfer of power utilized today that it is accepted as a matter of course in machine tools.

Cranes and general-purpose lifting devices are widely used, of necessity, to move heavy workpieces. Sometimes, a general-purpose lifting device is not most economical for a specific job. In one case an operation of drilling about 110 holes was performed on marine gear casings weighing from 1000 to 2000 pounds each. It was necessary to set up each piece six times with a crane to complete the work on it. Then a special power driven indexing table was built to position the pieces at the machine. It saved from 24 to 32 hours each week on the job.

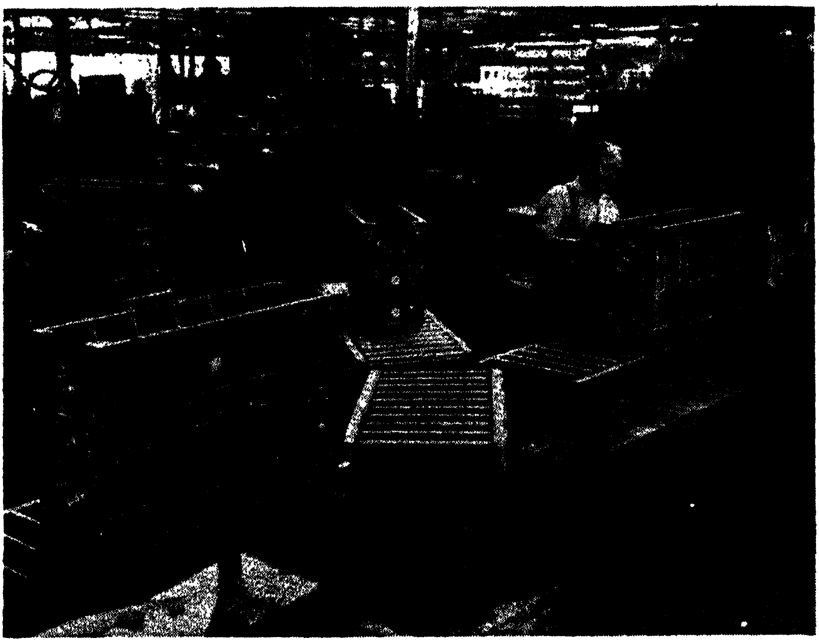

Fig. 38. An elevator in a conveyor. The blocks shown at the left rear come on a conveyor at a lower level than required for the machine at the right. Operator effort is reduced by the air-operated elevator that raises the blocks to the height of the front conveyor, from which they slide directly into the machine. (Courtesy Detroit Diesel Div. General Motors Corp., Detroit.)

The positioner in the lower view of Fig. 35 is power-operated to save manual effort.

Conveyors of various types are common in high-production plants to expedite the movements of parts, small and large. Where parts are heavy, shifting of pieces may still require a heavy expenditure of effort. To alleviate the effort in turning engine blocks over, a tipover device is shown in Fig. 37. In Fig. 38 the machine is loaded at a higher level than the pieces occupy on the conveyer, and a portion of the conveyer has an elevator inserted for lifting the blocks. In addition to contributing to the relief of operator's burdens, these examples are considerations in helping the flow and movement of materials.

Air or hydraulic clamping devices are quicker in action, more constant in clamping power, and more convenient than hand operated clamps and save human energy. Where several clamps are used in one fixture, arrangements can usually be made to close them simultaneously by air or hydraulic means. The motor device for air or hydraulic clamping is a cylinder and piston. Two types are available; the rotating and nonrotating. Rotating cylinders are used on revolving spindles. One is shown in Fig. 13. Chucks operated by such cylinders are shown in Fig. 17. Nonrotating cylinders are depicted in Figs. 20 and 53.

Considerable savings in time are possible from the use of air or hydraulic clamps. A large company conducted a survey to find the difference in time between air and manual chucking. For round pieces, light enough to be lifted into the chuck by hand, the following results in Table 1 were reported:

TABLE 1[7]

COMPARATIVE TIME WITH AIR AND MANUAL CHUCKING

Size Chuck	*Manual Operation (Min.)*	*Air Operation (Min.)*
6	0.25	0.05
8	0.35	0.10
10	0.45	0.10
12	0.50	0.10
15	0.80	0.12

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[7] As reported by Harry L. Stewart, "Air and Hydraulic Clamping for Jigs and Fixtures," *The Tool Engineer*, Dec. 1948, Vol. XXI, No. 6, p. 25.

The average ratio of chucking time between manual operation and air operation is four to one. As far as speed is concerned, hydraulic operation is a close rival to air operation.

In addition, air or hydraulic clamping can be controlled more uniformly than manual clamping, thus reducing tendencies for workpiece breakage or distortion and insufficient grip.

The savings so far indicated are in addition to the energy and strain saved the operator. It has been proven conclusively that operator fatigue can be greatly reduced by the use of air or hydraulic clamping means where large exertions must be made. If the operator is called upon for heavy manual labor, his efficiency is found to dwindle appreciably with time on a shift. This is not the case where the effort is taken over by air or hydraulic devices. Also physical impairment has been caused by operators straining themselves on large manual clamping devices.

It should be remembered that air or hydraulic devices are more costly to install and operate than conventional manual devices. Although there should be justification for their use, air or mechanical devices are not reserved necessarily for very high production. Air chucks on engine and turret lathes handling a large variety of work are not uncommon. On the other hand, cases may be cited even for high production where the use of complicated powered devices add so much complication and expense as to make them uneconomical.

Where such means are justified, the general rule, as stated by Stewart,[8] to be followed in choosing between air and hydraulic devices is as follows:

> If your application requires a large amount of power, a minimum amount of space, average cycling, and normal heat, use hydraulics; if your application requires a medium amount of pressure, plenty of space, high cycling, high temperatures, use air.

Lightening of burden includes those means whereby the physical load placed on the operator is reduced. Where the load is at a feasible minimum, means to take up part or all of it may be adopted, as explained in the first part of this section. If the object of burden is a workpiece, not much can usually be done to reduce its bulk as that is determined by necessary specifications, and the use of supplementary power must be made if the piece is too cumbersome.

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[8] *Op. cit.*

Often, however, tools add excessively to the load. Jigs enclosing the workpiece may have to be moved about or turned over. Good design dictates construction that is as light as possible in keeping with adequate strength and rigidity.

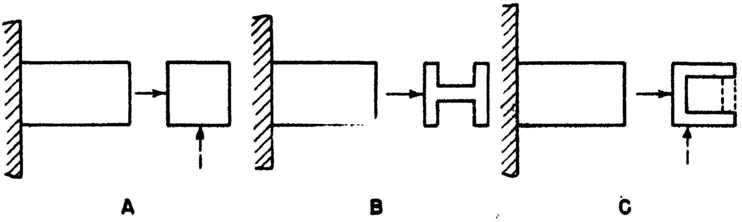

Fig. 39. Proper distribution of material in tools. This is an important factor in securing adequate strength and rigidity with the least weight.

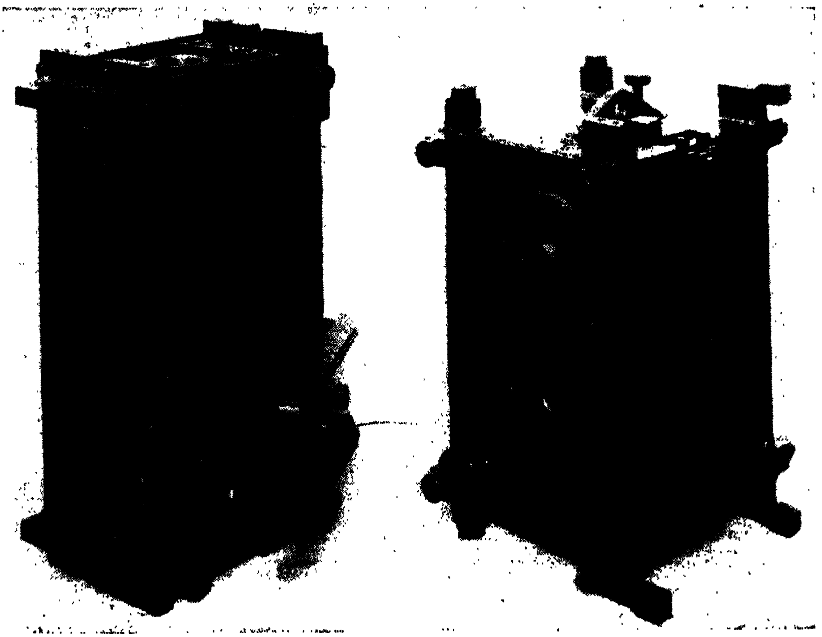

Fig. 40. Two examples of box jigs for drilling, reaming, or spot-facing a number of holes related to different surfaces.

The body of each jig is of welded construction, which provides a minimum weight with adequate strength and rigidity. For added strength, reinforcing strips are welded along the panels. Details subjected to wear, like the feet and bushings, are hardened, ground, and pressed or fastened with screws in place. (Courtesy Lincoln Electric Co., Cleveland.)

The study of the strength of materials tells us that the unit stress of any structural member subject to bending varies from a maximum at the outer fiber to zero at the neutral axis. It is, therefore, logical to place more material at the outside and remove some of that near the neutral surface to achieve maximum strength and rigidity for a certain amount of material. In Fig. 39, hypothetical members to resist a force F, or components F_1 and F_2, are shown. At A the square or rectangular section uses the most material for a given stress or deflection. For a force in one direction, the I section of B uses theoretically the least material, but modifications like the T section may give practically the same effect with easier construction. For forces in two directions, the box section is theoretically the most economical of material, but others, like the U section, approach it and may be more desirable for certain applications.

In addition to the shape, the material used and the method of fabrication are considerations in achieving desired properties of tools with minimum material. Welding of steel plates to form jigs, fixtures, gages, and other tools is a means of securing these attributes.

The two jigs of Fig. 40 are examples of welded construction of machine steel plates for lightness with strength. The large areas are reinforced by welded strips. Surfaces subject to wear, like bushings, legs, and locators, are attached to the frame.

The fixture of Fig. 41 is another noteworthy example of light weight, yet sturdy construction. Holes drilled in the frame reduce weight and facilitate grasping the fixture.

Conservation of skill

Skill may be conserved by reducing the level of skill necessary to do a job and by utilizing the skill available to the utmost. Two basic principles of tooling applicable to this consideration are:

1. Transfer of skill.
2. Advantage of perception.

Transfer of skill to tools and machines may be done by:

a. Building skill into tools.
b. Making tools foolproof.
c. Providing means to compensate for variations in workpieces.

The drill jig has been cited as an outstanding example of building skill into tools, since it enables a person considerably less skilled than a toolmaker to drill holes in accurate positions in a piece. Built-in skill is a widespread characteristic of machine tools, fixtures, jigs, dies, gages, and so on. The problem is that of selecting and prescribing the features of tools which most efficiently utilize the principle of transfer of skill for a particular purpose.

A basic rule of tool engineering is that all tools must be foolproof. That is, they must be constructed so that the workpiece can be inserted in only the correct position in its holding device or the tools can be brought to bear in only the right way. Anything less exacts a needless exercise of skill. An example of a foolproof jig is that of Fig. 42. The jig must fit on the casting in a definite posi-

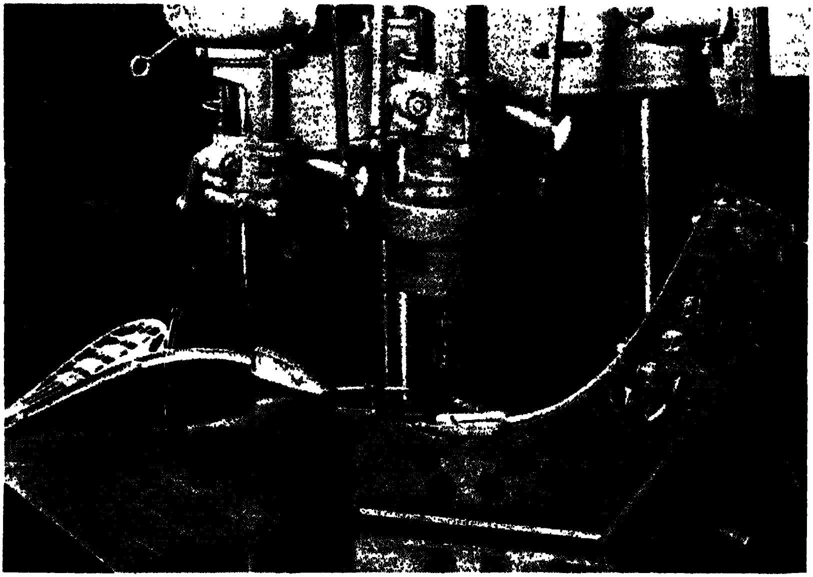

Fig. 41. A fixture for drilling and tapping. The curved casting has three holes to be drilled and tapped, all at different angles. To facilitate this, the fixture is made with three lower faces having pins, the ends of which are in planes at right angles to each hole. The curved upper face of the fixture fits the casting that it holds against turning. Each of the holes is brought into correct position under the drill and then under the tap by merely rocking the light fixture onto each of the three sets of pins successively and shifting the fixture sidewise. Each of the holes is spotted in making the casting, hence, the drill finds itself readily, and no drill bushing is required. The pins prevent chips from interfering with proper leveling of the fixture in each position. (Courtesy New Jersey Zinc Co., New York.)

tion. Foolproofing results from the position and size of the end-locating block, which will not pass the casting if the jig is put on wrong. The fixtures of Figs. 43 and 44 also are made so that it is not possible to insert the workpieces backwards.

Rough workpieces vary considerably in comparison with finished pieces. To maintain a reasonable relationship between the rough surfaces that will remain and the finished surfaces which are imposed on a piece, a skilled mechanic checks and aligns each piece to compensate for variations. This procedure is too slow and exacting for production. For the unskilled workman, plans are made so that he may locate each piece in a definite position most fitting to its characteristics, so that the clamping means will engage each piece securely and so that other surfaces than the locating surfaces can be reinforced by nondistorting supports. This brings into use the principles of location presented in Chap. 13 and the ability to resist deflection discussed in Chap. 14. A jig embodying these principles is shown in Fig. 43. Each part is nested in the jig to

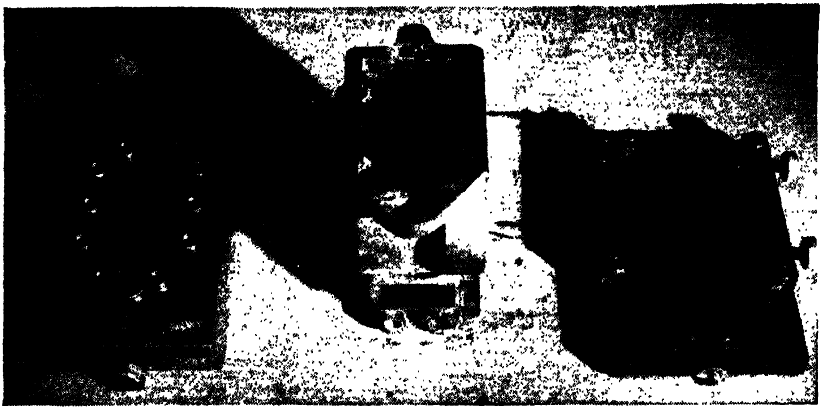

Fig. 42. An example of a foolproofed jig. The plate jig is shown in two positions on the right and left of the small cylinder block casting on which it is used. The jig locates a number of holes of different sizes as shown in the top view on the left. It is necessary to foolproof the jig so that the positions of the holes will not be reversed. The screws, shown in the jig in its upside-down position on the right, pull the locators against the side of the casting. The end locator bears against the large end of the piece and clears the small lug there. If an attempt is made to fit the jig 180° from its correct position, the end-locating block will not pass the tapered end of the casting base and will prevent the jig from going on in the wrong position.

centralize the hole with the body through which it is drilled. Equalizing locators compensate for variations to permit uniform clamping. In addition, the upper locators foolproof the jig so that the pieces can be inserted in only one way.

Another example of compensation and foolproofing is shown in Fig. 44, for drilling the wrist pin holes in the bosses at the small ends of two connecting rods at once.

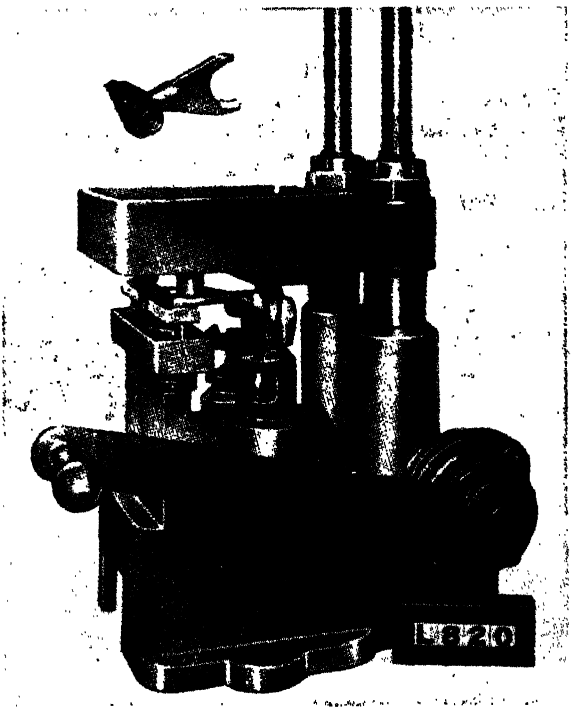

Fig. 43. A standard universal jig body adapted to drill a hole in each of two shift forks. This design illustrates means of controlling the effect of workpiece variation. In the first place, each part is nested in tapered locators to centralize the hole with the body through which it is drilled. Second, the locators in the lower adapter are compensated to allow for variation from piece to piece and provide equal clamping effect upon each piece.

The upper locating fingers take the pieces in only one position and thus foolproof the jig.

The head is raised for placing or removing the workpiece and lowered for clamping. The projections above the head are guide posts for a drill head. (Courtesy Swartz Tool Products Co., Detroit.)

Advantage of perception includes means to increase the ability of a workman in visualizing the going state of conditions in an operation. Usually when the perception of a job is magnified, the skill necessary to do it is reduced. If measuring instruments are crude, more reliance must be placed upon judgment and "feel" in determining dimensions. That requires a higher order of skill than if the workman has devices which tell him clearly and reliably what the dimensions are. This concept is demonstrated in Fig. 201 in relation to cylindrical grinding. Close tolerances in grinding are affected by many factors; the condition of the machine, the condition of the workpiece, the wear of the wheel, and the manipulation of the machine. A highly skilled operator is able to work the machine in

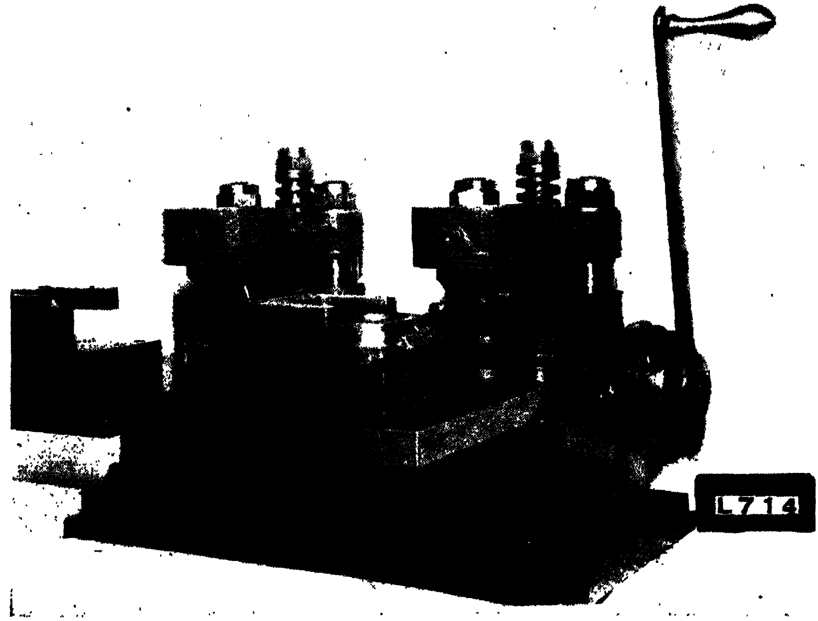

Fig. 44. Two jigs arranged in tandem and operated from one control point. The bosses at the small ends of the connecting rods, in which the wrist pin holes are drilled, are automatically centered by tapered locators in the heads when clamped. Variation between two parts in the jig is taken care of by the clamping springs, shown at the rear with their dust covers removed, through which the clamping forces are transmitted to the heads from the single clamping lever. The heads are held irreversibly in place by the fixture lock through which the handle moves the linkage. (Courtesy Swartz Tool Products Co., Detroit.)

very much the same way for each piece and estimate from the grinding action what is taking place. But the type of gage illustrated reflects instantaneous behavior of the operation and aids in obtaining the results with the exercise of less skill than would be required without it.

Combination of operations

The combination of operations is one of the most profitable ways of eliminating elements. It may be done by:

1. Simultation.
2. Integration of cuts.

Simultation involves doing two or more elements of an operation at the same time. That includes taking two or more cuts simultaneously or arranging for the machine to be working at the same time

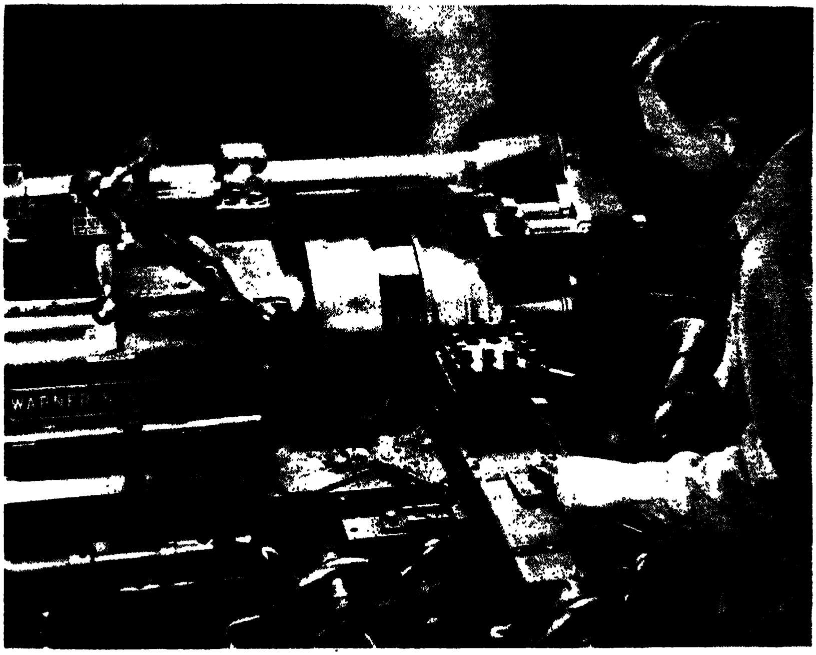

Fig. 45. A turret lathe tooled for multiple cuts from the hexagonal turret, combined with a cut taken by a tool in the square cross-slide turret. (Courtesy Warner and Swasey Co., Cleveland.)

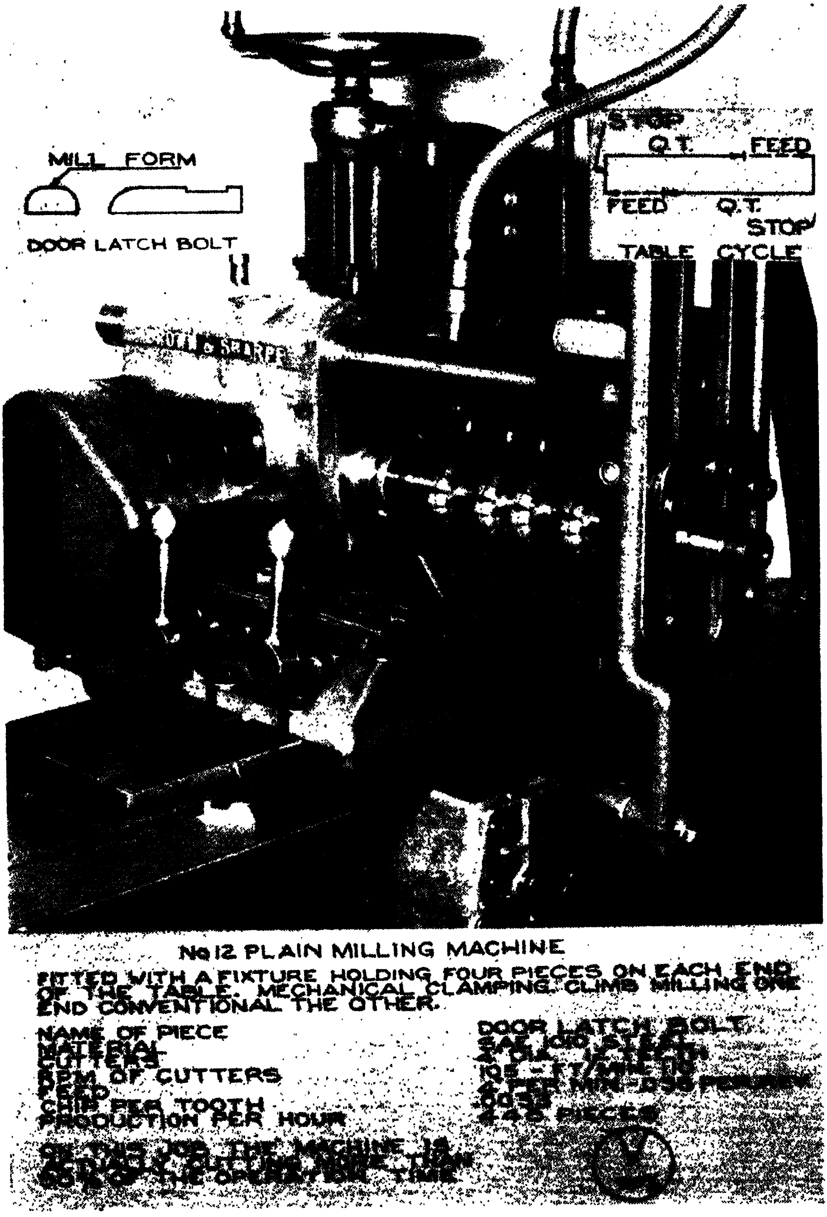
MILL FORM
DOOR LATCH BOLT
STOP
Q.T.
FEED
FEED
Q.T.
STOP
TABLE CYCLE
No 12 PLAIN MILLING MACHINE
FITTED WITH A FIXTURE HOLDING FOUR PIECES ON EACH END OF THE TABLE. MECHANICAL CLAMPING. CLIMB MILLING ONE END CONVENTIONAL THE OTHER.
NAME OF PIECE
MATERIAL
CUTTERS
RPM OF CUTTERS
FEED
CHIP PER TOOTH
PRODUCTION PER HOUR
DOOR LATCH BOLT
ON THIS JOB THE MACHINE IS

Fig. 46. Right- and left-hand fixtures on a milling machine, one working while the other is unloaded and loaded. The table stops after each cut so the operator will not be endangered by its reversing before he finishes loading. (Courtesy Brown & Sharpe Mfg. Co., Providence, Rhode Island.)

the operator is engaged productively. It is a duty of the tool engineer to provide the means for simultation where the latter is justified.

Simultation is a common objective of special setups and is exemplified in Figs. 30, 68, 147 through 150, 154, 155, and 156. However, advantages of simultation may quite often be realized from resourceful tooling of standard machines. Much of the economy

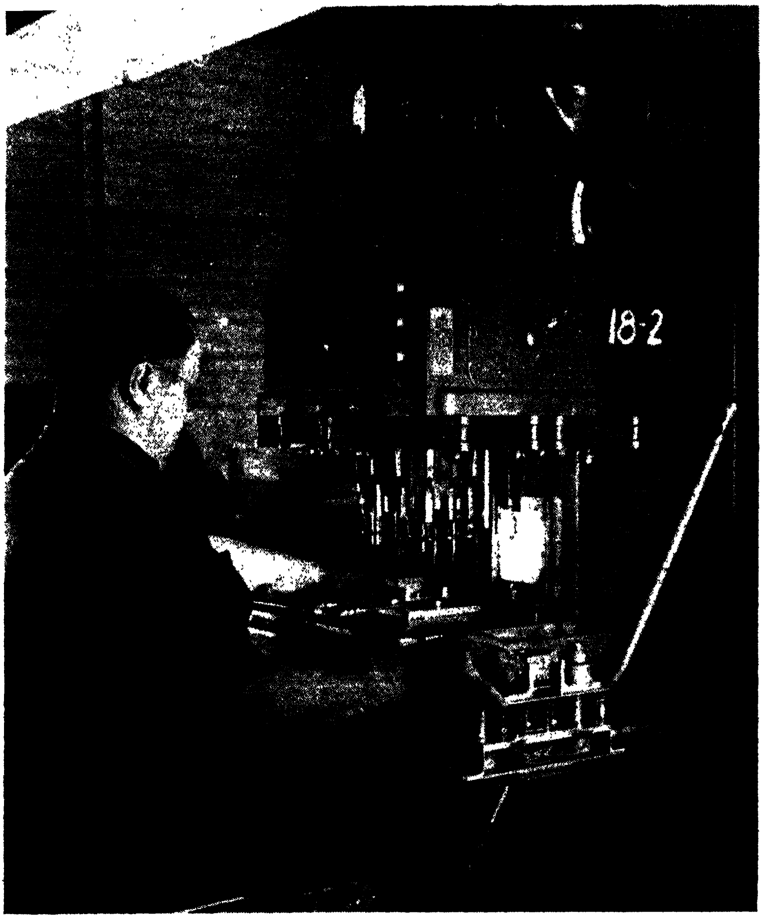

Fig. 47. An air-cleaning fixture at the side of a tapping machine. Two operations, tapping and cleaning the threads, are done together. (Courtesy Penn Electric Switch Co., Goshen, Ind.)

of turret lathe work is derived from multiple and combined cuts. Figure 45 shows a turret lathe, tooled for multiple cuts from the hexagonal turret combined with a cut taken by a tool in the square cross slide turret. The same idea is carried over into automatic lathes.

For milling, a standard machine may have a fixture installed at each end of the table so that one may be unloaded and loaded while the other holds the piece being machined, as shown in Fig. 46. The indexing table, which is a standard attachment, holds two fixtures for the same effect on the machine of Fig. 231. A cleaning fixture is shown installed beside a tapping machine in Fig. 47 to enable cleaning to be incorporated into the tapping operation.

Integration of cuts requires means to incorporate several cuts successively in an operation, even though they are not done simultaneously. That this is a means of eliminating elements is obvious from comparison of any combined operation with the separate operations otherwise necessary to make the individual cuts. Thus, if drilling is done in separate operations, elements of loading, positioning, and unloading are needed for each operation. But if the several holes are drilled in one operation, all but one loading and one unloading element is eliminated. One setup instead of several is likewise incurred.

A common device used for integration of cuts is the box jig, shown in Fig. 40, in which a number of dissimilar holes may be drilled, bored, or reamed in a workpiece in one operation on a standard drill press.

There are a number of general variations to the problem of supplying the equipment for machining more than one surface of a part in the same operation. Quite often the surfaces are oblique to each other. Sometimes it may be desirable to provide means to position the surfaces with respect to the conventional positions occupied by the tools; at other times, it may be advantageous to hold the work in a normal position and arrange the tools and machine to suit. The most economical arrangement for any specific case depends upon the considerations involved, such as the quantity, actual relationships between the surfaces, the type of process, etc.

Box jigs like those of Fig. 40 have feet on the sides at right angles to each other to position holes occurring in the same relationship. Holes, or surfaces, may be at other than right angles. Such is the case of the holes in the curved casting of Fig. 41. That fixture has three base surfaces with legs in planes to position each of the holes vertically. A frequently met consideration is to proportion the legs so that all the holes can be drilled to their desired depths with the same setting of the stop on the drill press spindle.

An ingenious arrangement for positioning a piece so that two oblique holes may be drilled and then tapped is shown in Fig. 48.

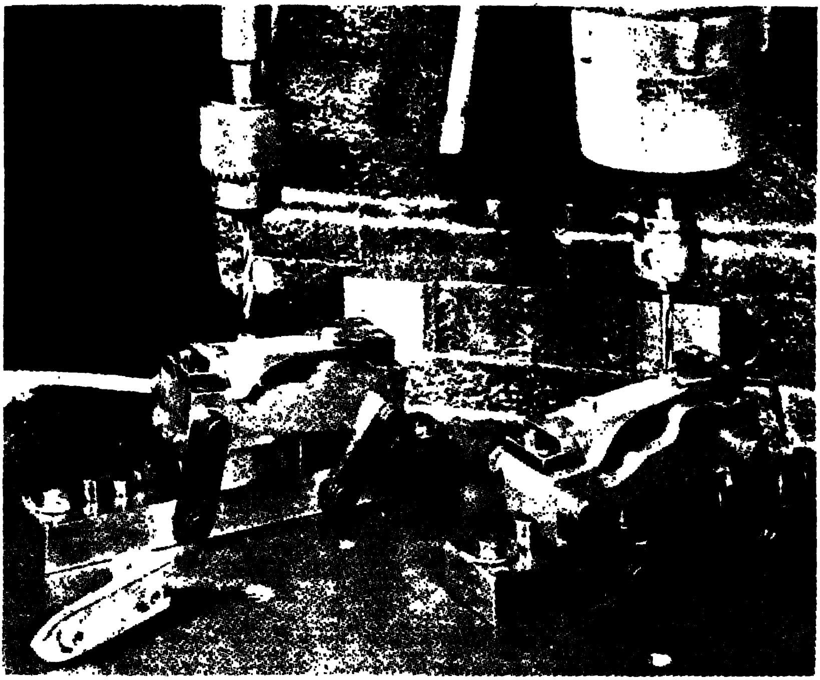

Fig. 48. Drilling and tapping fixtures. These simple fixtures are used for drilling and tapping holes in trunk hinges. The parts nest in the locators so that they cannot turn or rock. The two holes to be drilled in the bosses and then tapped are not parallel, so the holder blocks are mounted on swinging links pivoted to the bases bolted to the drill press table. When the holder block is swung to the right against one stop, the hole at one end comes under the tool. Then the block is swung to the left against another stop, bringing the other boss into line. In such position the piece is differently inclined to bring the axis of the boss into line with the axis of the tool. Four to five hundred castings are drilled and tapped per hour by one operator, using first the drilling and then the tapping fixture. Had the holes been parallel, they could have been cored conveniently to size to eliminate the drilling and a simpler sliding fixture like that of Fig. 31 could have been used.

The simple tilting mechanism is built into the fixture and gives automatic positioning with respect to the tools.

Auxiliary devices may be used with or incorporated into jigs and fixtures for the purpose of consecutive positioning. For drilling angular holes, jigs are sometimes used with cradles in which they are held in appropriate positions, like that of Fig. 49. For lightness, large cradles may be made of hardwood faced with sheet metal.

Where permanent legs holding a jig at an angle may be in the way of other positions, swinging legs can be used instead, to be turned out of the way or latched in place when needed.

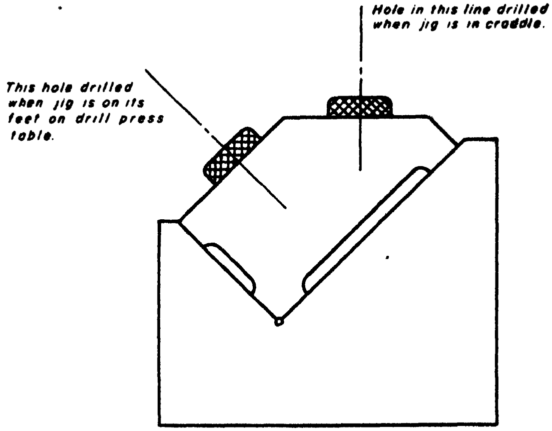
Hole in this line drilled when jig is in cradle.
This hole drilled when jig is on its feet on drill press table.

Fig. 49. An outline of a jig for angular holes with a cradle for positioning it advantageously.

One of the commonest positioning means for consecutive placement is indexing. There are three general types of indexing devices: the trunnion, rotary table, and straight line. Figure 36 shows the details of a trunnion-type indexing fixture. Another application is shown in Fig. 154. Applications of rotary-table indexing are illustrated in Figs. 68, 142, 147, 155, 156, and 231. A fixture utilizing straight-line indexing is part of Fig. 143.

For some types of operations, like milling, it may be desirable to present several surfaces to be machined in suitable positions to save individual setups. Examples of such arrangements are shown in Figs. 70 and 148.

Instead of positioning the workpiece to conform to the conventional positions of the tools, the alternative of holding the workpiece in a normal position and rearranging the tools to suit has been suggested. The latter usually requires special features of the machine tool. Adaptations of machine tools for that purpose are shown in Figs. 68 and 149.

ECONOMY OF INDIRECT COSTS

Reduction of costs of auxiliary services

So far attention has been focused upon ways and means of securing economy in the direct effort expended upon production. It must not be forgotten that all direct production effort is dependent upon and closely linked with a number of auxiliary functions and that it is as important and profitable to minimize their costs as those of the direct effort. The interest of tool engineering is in furnishing the equipment to minimize the indirect costs and enable the auxiliary functions to serve the direct effort most efficiently. Important auxiliary services are:

1. Inspection
2. Scrap disposal
3. Setup and change over
4. Cleaning
5. Maintenance, upkeep, and repairs.

Inspection in production is done with gages, which normally originate with the tool engineer. He naturally has the responsibility of furnishing gages which serve most economically in the routine of inspection operations in the same way as tools are expected to do in the productive operations. That means that gages should conform to the principles of motion economy, prevention of undue strain, alleviation of heavy labor, and conservation of skill; and most of the principles under those headings are fully applicable to gages just as much as to tools. But, in addition, inspection can be co-ordinated profitably with production by providing suitable gages at the workplace. Benefits may be derived in two ways, namely:

a. Through simultation, to provide means for the production operator to perform at least a preliminary inspection while the machine is working, during time when he might otherwise be idle. Even if inspection checks are also made later, the constant attention of the operator helps relieve the burden upon inspection as the quality is more likely to be acceptable, and undesirable trends are immediately shown up and can be corrected.

b. Through provision for checking the finished workpieces before they are taken from the machine, even if some time is added to the operation. In many cases a net gain is possible from the savings in rework and the reduced cost of later inspection and handling.

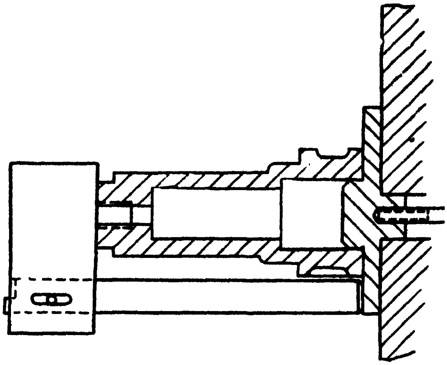

Fig. 50. A typical face plate fixture for second operation work. The sketch shows a flush pin gage that might be supplied to enable the operator to check the over-all length of the piece directly from the locating surface before each piece is removed from the fixture after the small end has been faced.

In the operation shown in Fig. 30, a gage in front of the die enables the operator to check each piece while the ram of the press is in motion.

Figure 50 shows a flush pin gage for checking the over-all length of a piece before it is taken from the fixture on which the small end is faced. A gage like this can be used with one hand more quickly than a standard depth micrometer. It represents a definite addition to the tooling, as probably a snap gage or length gage would be supplied for actual inspection of the piece off the fixture. Its cost of fabrication and use may well be more than made up in many cases by the savings in inspection and by the assurance it gives the operator. In some plants almost any such simple gages serving the same purposes are supplied without hesitation wherever they are adaptable because of the good record that similar ones have had.

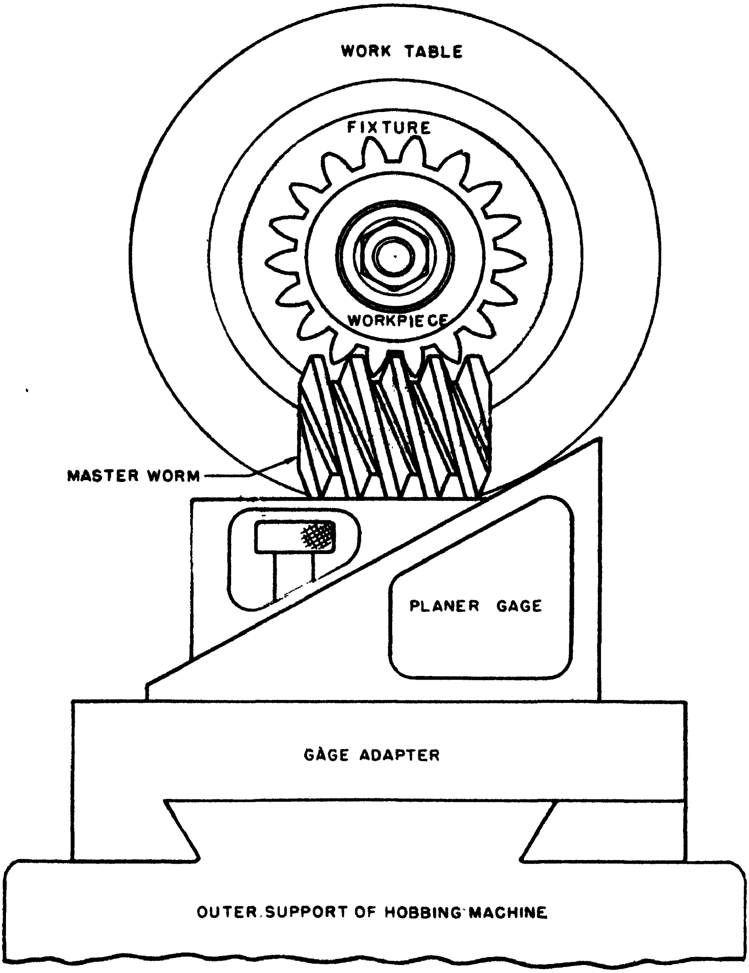

Fig. 51. A convenient, yet inexpensive, attachment to a hobbing machine, used for checking a worm wheel before removal from the arbor. A planer gage is clamped to the way of the outer support, which is always a fixed distance from the centerline of the work arbor. A master worm is engaged with the work piece, and the movable member of the planer gage is brought up to the worm to check the center distance. The height from the face of the hub to the center of the throat and the alignment of the worm can be checked by a height gage. A time saving of 50 to 75% in checking worm gears has been reported. (Courtesy of *Production Engineering and Management*; attributed to Edgar P. Wetzel.)

A convenient yet inexpensive gaging attachment made up of standard details is shown in Fig. 51 for checking worm wheels before they are removed from the hobbing machine on which they are cut. A time saving of 50 to 75 per cent in checking the worm gears was reported from use of the equipment.

Scrap disposal is an item of expense even after the chips or refuse have been removed satisfactorily from the vicinity of the actual work being done. Some thought should always be given to means for:

a. Separating scrap from good parts by simple mechanical means if the operation is such that the two become mixed.

b. Economical removal of the scrap from the machine to actual storage in the plant for ultimate disposal.

Too often, scrap material is allowed to drop into the same containers with the parts coming off a machine, and the two must afterwards be separated. Simple mechanical means can usually be provided to keep the scrap separate from the good parts. On a punch press in one plant, two chutes are placed so that the scrap material falls into one and the parts are directed down another one as the operation is being performed.

A strip fed through a compound die may have the blanks punched out and then be neatly reinserted in the strip by the action of the pressure plates. To twist these pieces again out of the strip from which they have been severed is tedious. However, it has been found that if the strip with the pieces in place is passed between a pair of rolls and then is bent as it leaves the rolls, the inserts will fall out undistorted. The scrap strip may then be cut or rolled up for disposition.

For low and moderate production chip removal from a machine may have to be a conventional manual operation as typified in Fig. 52. However, convenience which will help this form of removal should not be disregarded. Large and accessible depositories like that of Fig. 53 are desirable. Sometimes a tray may be provided to collect the bulk of the chips, as in Fig. 231. The tray can be removed and dumped at intervals.

For high production with a large rate of stock removal, elaborate equipment to take the chips from machines may be justified. Some machines have conveyers built into them to carry out refuse to external bins. In one artillery shell plant during World War II, Although certain tool details need to be fastened to the whole tool in a way so that they can be released readily when desired, care must be taken that the security of the details is not compromised. If details become loose, shift, or drop out, repairs are usually necessary. To avoid the cost of such occurrences, details should be locked securely in place. For instance, locating or set blocks are usually held on with screws, but are also doweled, so that if the screws become loose, the blocks will not shift and if the blocks are removed, they can be put back readily in the same locations. Another example is furnished by the section of the indexing mechanism of Fig. 197. Although the wear bushings are pressed into place, their heads are put so that there is no chance of their coming out, unless the mechanism is intentionally disassembled.

Repairs can be speeded and their cost reduced by the use of commercially obtainable standard details and tools whenever possible.

Adequate lubrication is perhaps the largest potential contribution to long, low-cost performance of any machine. Therefore, in the selection of machinery and equipment, the provisions for lubrication should not be overlooked. Also, tools deserve more attention on this score than they have received in many cases. Since some tools are not in themselves power driven, too little attention has been paid to means for lubricating their moving parts. Various ways and means of lubricating machinery make up a large subject and no attempt will be made to go into its technicalities here, which are well covered in many texts of machine design. The various possibilities available for any installation should be examined from the standpoints of efficient action and economy of utilization.

Promotion of safety

The nature of the penalties for a lack of adequate safety measures is well expressed by John I. Junkin in his treatise on *Power Press Protection.*[9] He has said:

> The story of the industrial accident is a story of profit and loss, for every accident is not merely an individual tragedy but is also an equally serious production and financial loss. Just as no employee can ever be fully compensated for the loss of a hand neither can the employer ever recover the

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[9] J. I. Junkin, *Power Press Protection.* Louisville, Ky.: The Junkin Safety Appliance Co., 1946.

cost of this compensation. The loss shock will be cushioned for him by his insurance carrier but in the end he will pay the full bill with interest.

In the shop the accident victim is viewed with profound shock and pity by his fellow employees. For hours or days they will be haunted by his crumpled form or mutilated hand. Efficiency falls and production lags. A feeling of uneasy tension will prevail for days for there is always a fearful question of who will be next. The accident victim also appears in the accounting department. Here however he is only a small part of a very neat and very substantial figure which appears on the debit side of a ledger. Here he becomes a part of profit and loss and will remain long after the circumstances of his individual accident have been forgotten.

The safety movement received a great impetus during the war years, which has carried over into peace production. Government contracts required that a set minimum standard of safety practice be maintained and many in industry learned for the first time that good safety was after all good business.

High among the major causes of all industrial accidents is the power or stamping press. These presses scattered as they are throughout every type of industry take an enormous toll each year. We who have devoted ourselves to the guarding of these presses wish it were possible to say that we have all the answers to the problem. We haven't. The answers we do have are these learned through years of experience with power presses and through our own successes and failures in providing safety guards for them. Each operation and each press as a rule presents a separate and distinct problem due to the varying size and general character of the objects produced and the consequent variety of presses and dies used. The human mind is not capable of performing twelve to twenty thousand identical operations a day without momentarily wandering. One careless motion during these mental lapses and the operator may be crippled or handicapped for life. Codes and regulations drawn by state industrial commissions and insurance companies as a guide to proper press guarding are all too often found not practical or specific enough for general use.

Factors which play an important part in the general problem are press maintenance, feeding methods, safety guards, inspection and supervision, operating personnel, lighting, and general housekeeping. Careful consideration and a satisfactory solution of each is necessary for the creation of any completely satisfactory experience. Failure in any one may mean disaster. . . .

Those who permit slipshod maintenance on power presses should realize that the cost of the average press accident in compensation alone is approximately $480.00 while that of the minor repairs which might easily prevent this accident cost only a few cents.

The tool engineer should appreciate all phases of the general problem of industrial safety, but primarily he is responsible for furnishing the equipment necessary for protection. This concern may be divided into three considerations of:

1. Safeguarding the working zone (point of operation guarding).
2. Safety of controls and machine mechanisms.
3. Protection against moving parts (power transmission guarding).

The problem of *safeguarding the working zone* is as a general rule different for operations in which the stock is fed automatically or semi-automatically from what it is if the workpieces must be placed individually and the operator is liable to come within the area of action of the tools.

On high-production primary operations where the raw material is in suitable form, insertion of the stock into the machine may be automatic. While the tools are acting, there should be no reason for the operator getting into the danger zone, but barriers must be erected to prevent accidental entry. Some punch press operations are of this type. Where automatic rolls or hitch feeds are used, care must be taken to see that not only the point of operation but also the feeding rolls or mechanism are fully enclosed. For manual feed, suitable protection must be provided to keep the operator's hands out of danger. It is usually possible and always preferable to include the necessary safety features in the plans for the die. A well-guarded continuous press operation in which the die is enclosed by a barrier is illustrated in Fig. 56. The barrier allows the operator to work within close proximity of the die without actually getting into it while it is set for operation. If he must have access to the die, the barrier can be swung out of the way; but it is so connected to the trip rod that the pedal is disengaged from the clutch of the press when the barrier is not in place.

In the large majority of operations, the pieces must be fed individually. Protective arrangements for such operations fall into the following classes:

a. Devices for feeding the pieces at a point outside the zone of tool action with mechanical means to pass the pieces into position. These devices preferably include automatic ejection.

b. Automatic interlocking gate guards.

c. Sweep guards.

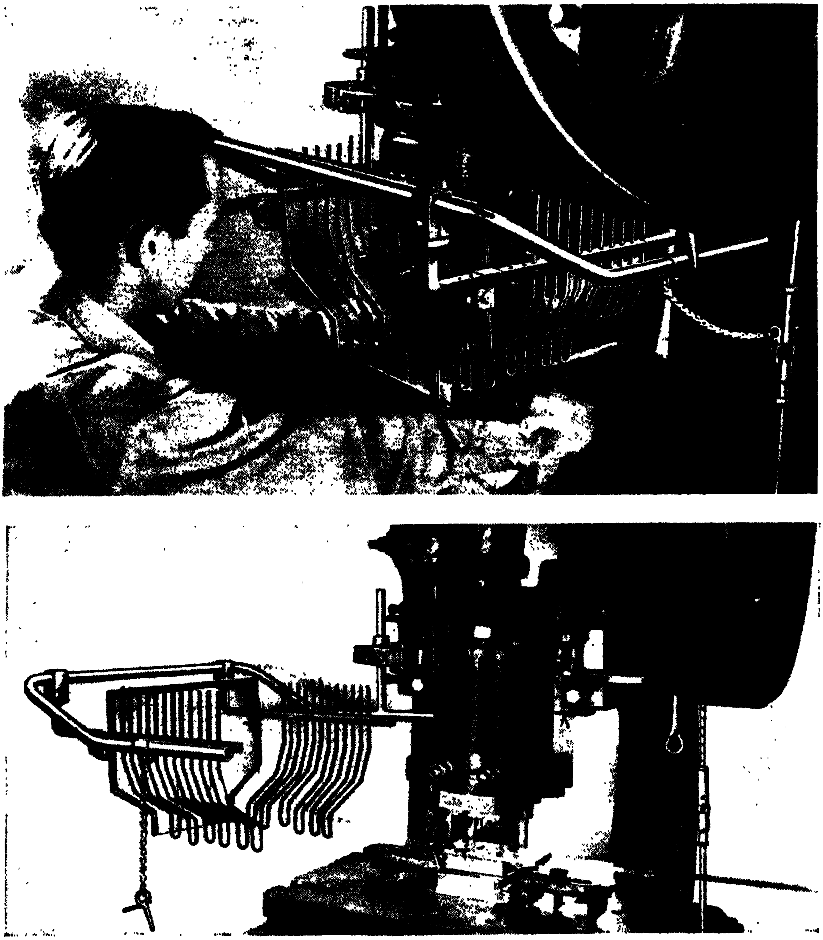

Fig. 56. A stationary barrier guard. For punch-press work where the stock is fed continuously in a strip, whether manually or automatically, stationary barriers adjustable to various size dies are often attached to the press frame. The barrier must allow the operator to get his hands close to the die, for hand feed, to locate and move the sheet or strip easily, and yet prevent him from inadvertently getting caught within the die itself. He must be able to see the work being done. A well-designed barrier can be readily swung out of the way to permit easy access to the die for adjustments. A key chained to the barrier is desirable for disconnecting the pedal from the clutch mechanism when the barrier is out of position, so the press cannot be tripped when the operator is working with the die. A properly proportioned barrier like the one shown can be adjusted to be effective for the full range of dies used in the press for which it is intended. One that is not so adaptable may be worse than none at all if at times it appears to give protection, but actually does not. (Courtesy Junkin Safety Appliance Co., Louisville.)

d. Electronic devices.
e. Pull out devices.
f. Nonrepeating arrangements.
g. Two-hand tripping devices and similar interlocking devices for two persons.
h. Tongs and other hand tools.

Junkin[10] says that:

> When one considers that 97 per cent of all press accidents can be traced to man failure and only 3 per cent can be attributed to any mechanical failure it is evident that by eliminating the human element you have gone a long way towards a solution of the problem.

Even if the pieces must be fed individually, it is desirable to keep the man outside the danger zone if at all possible. Where production is sufficient, special devices for this purpose are well worth-while. One arrangement is the dial feed, shown on a power press in Fig. 24 and on a milling machine in Fig. 32. The indexing arrangement for the milling operation of Fig. 231 is a variation of this idea. The clamping bolt of Fig. 216 is brought through the fixture so that the nut can be tightened and loosened on the side away from the cutter. Some of the remote feed arrangements are quite simple and comparatively inexpensive; for instance, the chutes of Figs. 25 and 26 over which the operator pushes the parts to the die. Even if the parts are not handled by the operator within the danger zone, a barrier should be provided around that zone to prevent accidental entry. Presumably the guards have been removed temporarily from the setups cited to help the photography. Another variation of remote feed is that in which the die block is mounted on a slide so that it can be pulled out, loaded, and slid under the punch so that the operator does not have to load it while it is under the punch.

The brevity of many runs, the cost of feeding mechanisms, and the nature of the work prevents the use of remote loading devices in many cases, and it is necessary that the operator place his hands in the danger zone to load or unload the work. There are still ways of providing protection, and for any case full use should be made of such as are necessary to provide adequate protection. One of these is the interlocking gate guard, based on the principle that one mechanical motion must be complete before the next is at all possible. A typical gate guard is shown on the press of Fig. 57. When the press is tripped, the gate descends. If the operator's arms present an obstruction its motion is stopped. The barrier gate must be completely down in a protective position and the operator's hands clear of the danger zone before it is possible to actuate the clutch mechanism. The guard may be used successfully on all secondary operations and on a limited number of primary operations but is not adaptable to extremely large presses nor to those employing a friction clutch.[11] The bottom rail of the guard is cushioned so as not to be a hazard itself.

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[10] *Op. cit.*

The sweep guard consists of a sweeping arm attached directly to the ram of a press through a cam and toggle connection. When the ram descends, the sweep is mechanically forced across the point of operation, clearing the operator's arms from it if they still are in the danger zone. The sweep must be well padded so as not to injure the operator, should it strike him. Shields are usually placed behind the sweep arm to prevent the operator working around it. This type of guard is successfully used on large presses.

Electronic devices may be placed so as to be interrupted by the operator's arms if they are in the press. They are arranged so as not to permit the press to be actuated until all obstructions are clear.

Pull-out devices jerk the operator's hands from the danger zone when the ram of a press descends. A cable is attached directly to the ram and runs over a suitable framework and a series of pulleys to bands attached to the operator's wrists. Co-operation of the workmen in wearing the wristlets, and checking the effectiveness of the pull out after each die change is necessary for satisfactory protection.

Most machine tools of the manufacturing type could be arranged to proceed automatically from one cycle to the next, but where pieces are loaded individually and manually it is very seldom that they are so arranged, even though some time might be saved in doing so. The reason, obviously, is that the operator may still be engaged in loading a piece when the machine indexes. Consequently, the usual practice is to make it necessary for the operator to start each cycle manually. Machines arranged in this manner are shown in Figs. 46,

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[11] *Op. cit.*

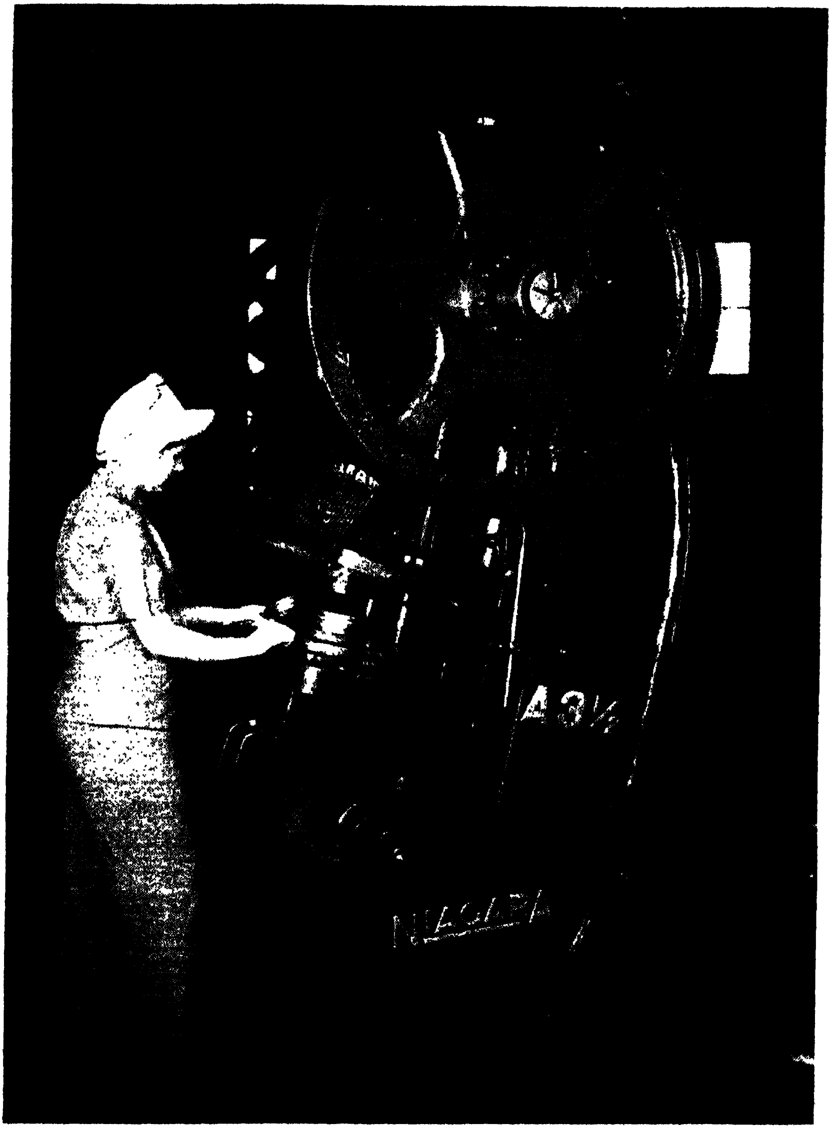

Fig. 57. A gate guard. Punch-press operations are among the most dangerous and require careful attention from a safety standpoint. One type of safety guard, illustrated here, is in the form of a pivoted grille that falls by gravity to enclose the die when the pedal for tripping the press is depressed. If the operator's hands or any other object are within the die space and prevent the guard from reaching the bolster plate, an interlocking mechanism prevents the press from operating. (Courtesy Junkin Safety Appliance Co., Louisville.)

68, 155, and 231. The danger of a power press repeating a cycle because the operator does not remove his foot from the pedal or from failure of the latch spring is prevented by nonrepeat attachments which make it necessary for the pedal to be returned to its original position before the press can be tripped again.

Two-hand tripping devices are arrangements requiring that both hands push buttons or press levers to start a machine. This requires that the operator remove both hands from the point of operation before tool activity can be started. An example is furnished by Fig. 17. Care must be taken that it is not possible to by-pass one control and operate a device of this kind by only one hand. An extension of the two-hand tripping idea is adapted to large presses where two or more operators are employed. Four, six, or more buttons are placed in line, depending upon the number of hands, so that all operators must signify their hands are free by pressing all buttons at once before the press can be tripped.

To place pieces inside a die or extract them, tongs, pliers, picks, and even suction cups are furnished for the operator to use instead of endangering his fingers. Such tools should not be hardened and in any event their use should be avoided, in favor of some other protective means, in connection with dies of such kinds that serious damage, or perhaps a dangerous wreck might result from their being caught.

In any kind of operation, the most desirable arrangement is one where the operator's hands are well clear of the cutters during the insertion, clamping, and removal of the work.

Safety of controls and machine mechanisms is a consideration not only for actual operation but also for setup and machine repair. On power presses a not uncommon source of accident is a falling ram. An adequate brake maintained in good working order is necessary to avoid this fault. Large presses should be provided with spring or compressed-air cylinder counterbalances to support the weight of the ram. Foot pedals are frequently covered by guards so that they are not depressed by falling objects or by being stepped on inadvertently. If a pedal guard is used, care must be taken that the pedal does not bind in it.

On some machine tools, speeds and feeds are changed by replacing pick-off gears manually. Many accidents have resulted from operators trying to do that before the machine has stopped or by the machine being inadvertently started while the operator is making the change. A safety measure on some machines is to connect the door of the change gear compartment to a switch so that the power to the machine is cut off whenever the door is open.

Protection against moving parts of machines calls for guards completely enclosing all belts, gears, shafts, flywheels to prevent the possibility of anyone around the machine making contact with them. All exposed screws, nuts, lugs, etc., whose moving might catch the operator, should be avoided; sharp corners and edges should be broken.

Safety should begin with the planning and designing of tools and equipment. The examples given of safety have been mostly about power presses. It should be remembered that on all kinds of machines there are hazards like those on power presses and the same principles are applicable to them to secure safety. Safety should be built into tools, from the removal of sharp edges which are able to cut and scratch the operator, to the complete guarding of quick and powerful actions which mangle and kill.

Co-ordination with movement of materials

Material handling costs are usually a sizable part of manufacturing cost and may even approach the actual machining costs in some cases. Material handling is not ordinarily within the province of tool engineering, but planning and tooling must not overlook any contributions that may be made to keeping down the cost of moving materials.

In a plant, machinery and equipment may be arranged functionally or in line. In a functional layout, machines are grouped in accordance with the functions they perform; milling machines in one group, lathes in another, and so on. Materials are moved from group to group. An operation sequence is essential, as far as it is possible, that minimizes long hauls and eliminates backtracking. Tooling sometimes has an influence upon these conditions, and such possibilities should not be overlooked. For instance, it may be desirable to provide tools for spot-facing surfaces on a workpiece while it is in the drilling machine group to avoid having to carry it over to the milling machines to have the surfaces finished.

For line production, the arrangement of machines is by product or component to be made. Thus, machines and equipment are placed in order of the operations to be performed on a part, like in a connecting rod department. With such a system, the balancing of operations is important for smoothness of flow and is largely dependent upon specifications of machines and tools.

As another consideration, several parts may be run over one line or their lines may intertwine to allow combined use of equipment. Efficient tool planning may often result in appreciable economies under such circumstances. An indication of such a situation is shown in Fig. 156.

Also, for line production the design and selection of tools and equipment adaptable to conveyers should be considered. Machines or tools may be arranged to constitute, in effect, stations on a conveyer line, like those of Figs. 37, 144, and 150. Where that is not entirely feasible, consideration should be given to making the holding devices amenable to easy transfer of the parts to and from the conveyer or other means of transporting them. An illustration of this is Fig. 38.

Workpiece mutilation in handling is a source of loss against which the tool engineer can often take effective steps. Scratching, scoring, and nicking of finished surfaces may be difficult to prevent, unless means are provided to guard against them. To keep parts from bumping together, simple racks or compartmentalized boxes are often furnished for articles handled in lots. Sometimes masks are desirable to cover highly finished surfaces. They need not be elaborate: cardboard for some cases, just oiled paper for others. Even though the precautions may be simple, provision must be made for them and the proper materials or devices must be on hand when needed.

Considerations of availability

The urgency of a project sometimes dictates the necessity of using a tool which is readily obtainable, rather than a more efficient one which may take time to construct or procure. At times, scarcity of certain materials or products may prompt the use of substitutes. Under such circumstances certain costs are likely to be higher than normal, but the possibility of achieving ultimate economy must not be overlooked. Delays in production schedules can bring about very serious losses. A single tool, machine, or type of material can hold up a large program. If a loss must be taken to realize a larger saving, it is logical to accept it. This is one consideration that has led to the widespread choice of welding for fabricating jigs, fixtures, and other tools which otherwise might be cast. Making a pattern, founding, and machining the casting consume several weeks, at least in most cases, whereas welded structures can be fabricated in a few hours to a few days. This is often helpful in getting a project under way and completed rapidly.

ECONOMY OF FIXED COSTS

Low construction costs

Low initial costs of tools, machines, and equipment can be promoted by:

1. Observance of principles of economical construction.
2. Use of standard tool details.
3. Adaptation of standard machine units.

The principles of economical construction include the following requirements:

a. A simple mechanism that will fulfill the requirements of a job is preferred to more elaborate devises.

b. Tools should have sufficient quality for the purposes intended, but should not be built too well.

c. Full advantage should be taken of the techniques of toolmaking to get low-cost construction.

d. Construct tools as much as possible so that they have a wide range of usefulness. The cost of one tool may thus be spread over more than one job and the expense of additional tooling can be reduced.

In many cases complex mechanisms are justified because the savings which they bring about in motion economy, conservation of effort, and elimination of attention more than offset their cost. However, the simplest device which adequately meets the requirements of any particular case is the logical one for it. For instance, the clamping of a piece may be done through the use of screw clamps, quick-acting but hand-operated cam or toggle clamps, or an air-operated cylinder and toggles or cams. The pieces are clamped in the fixture of Fig. 231 by a number of screw clamps at each station. More expensive clamping mechanisms requiring fewer motions and

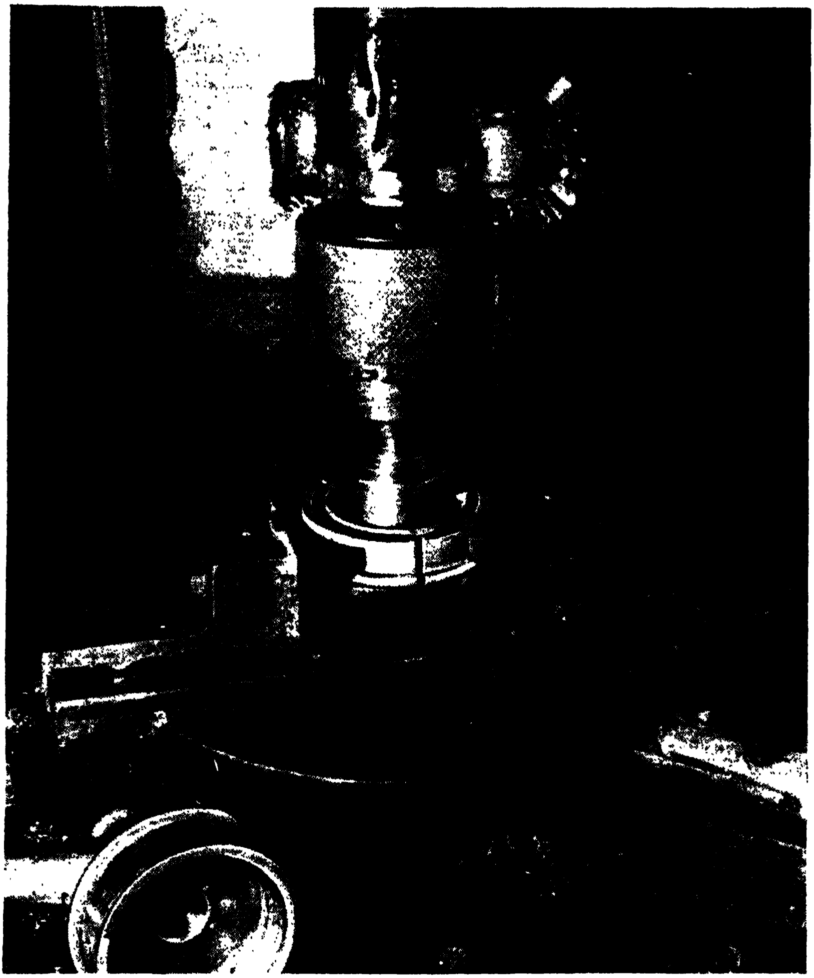

Fig. 58. A quick-acting fixture. In this fixture, jaws, which are moved by pins in eccentric slots in a pivoted disk, to which the handle at the right is attached, clamp the casting quickly and securely, and position it under the large tap, which is then lowered to produce a coarse thread in the cored hole of the casting. Jaw blocks fit a slide that holds them in line, but their ends, instead of being machined to fit the casting, are themselves cut from a die casting that happens to be available in a size that mates with the outside of the casting to be tapped. Except for the jaw ends, the fixture is one standardized for use in the shop producing the die castings. It can be adapted to fit many small castings by merely changing the jaw blocks, and has the advantages of quick operation and positive clamping in correct position. (Courtesy New Jersey Zinc Co., New York.)

less time and effort are entirely feasible for that job; in fact, have been applied quite often in the same capacity on the same kinds of parts. But in this case the operator has ample time to unclamp, unload, load, and clamp two pieces, while the machine is taking the cuts on the pieces in the other fixture. Any saving in clamping time that might be brought about by more expensive means is scarcely usable under the circumstances. However, if production is high enough so that another machine can be gainfully employed and the operator can be enabled to operate two or more machines, or be released for other duties during part of each cycle, then the more complicated and expensive clamping mechanism may be economical.

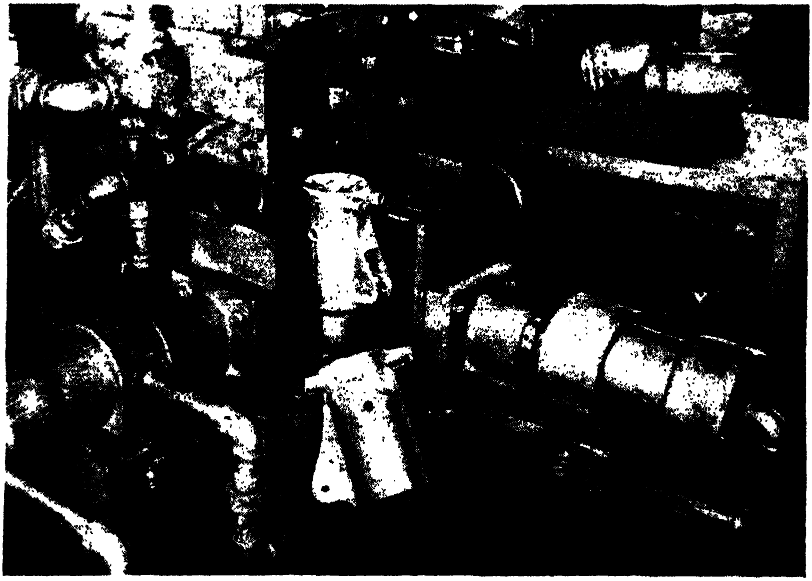

Fig. 59. An elaborate fixture that is actually a combined fixture and machine in which rams carrying one or more punches are advanced simultaneously from five sides of the casting. The punches shear flash from eleven through-cored holes and the five rams are advanced and withdrawn by merely operating a single valve in the hydraulic system. Although such a fixture is rather costly, its use is justified by the fact that large quantities of the motor-housing castings are required and can be put through the machine at the rate of thirteen hundred an hour (Courtesy New Jersey Zinc Co., New York.)

A less expensive fixture than that of Fig. 58 may be made to serve the same purpose by means of a screw, right-hand on one end and left-hand on the other, engaging nuts attached to the jaws to move them. Such a mechanism is slower than the one illustrated in Fig. 58. Since the cam clamping mechanism makes a direct contribution to reducing the time of each cycle of the operation, its complexity and cost is justified.

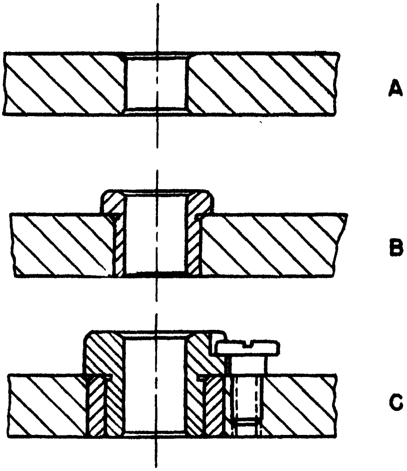

Fig. 60. Three methods of making a jig, depending upon service requirements. At (A) a template of soft steel is depicted. That is adequate to guide a drill if only a very few pieces are to be drilled. At (B) a hardened bushing is shown pressed directly into a soft-steel template. That is sufficient where there is little or no prospect of the bushing being replaced before the job is done. At (C) is shown a bushing which must be removed. It may be that wear is expected to necessitate replacement or the bushing may be slipped in and out during the operation. The guide bushing fits in a liner bushing pressed into the soft bushing plate.

An elaborate arrangement for punching a number of holes at once from five directions in a die casting is shown in Fig. 59. Simpler arrangements obviously are possible. The pieces might be placed consecutively in several dies, which together conceivably could be made more cheaply than the combination. In that case, direct costs would be more per piece. The large quantity of production justifies the costly device shown. On the other hand, it is quite possible that elaborate and expensive installations may fail to pay out even on high production jobs. Hinman[12] reports an instance where 12 hydraulic punching units, with quick-action compressed-air returns, were set horizontally for perforating the same number of holes through the outside wall of a drawn shell. This contrivance did not produce any better work than, and was not as fast as, a side-cam die in an ordinary punch press, although the elaborate affair cost ten times as much as the die.

It is obviously poor economy to try to make tools cheaply if they do not do a good job or if they do not stand up. On the other hand, tools are too often made with a life prospect far beyond that needed or with refinements which enable it to do a much superior job than is necessary.

A drill jig has one or more accurately located holes for guiding the cutting tool. If the number of pieces for which a jig is to be used is limited, the guide hole or holes may be bored in the soft body of the jig, as indicated at *A* in Fig. 60. If many holes are drilled from such a template, wear in the hole will defile the accuracy of the jig. For larger quantities, a hardened bushing is inserted in the template, as shown in Fig. 60B, and adds to the cost of the jig. The entire plate is not hardened unless it is small because resultant warpage is likely to upset the accurate location of the hole. If the bushing must be replaced, it is placed within a liner bushing, pressed into the soft plate to increase the life of the jig, as at *C*. The justified cost of each construction depends upon the extent of the service for which the jig is made. Obviously, the cost of the construction of *C* would be excessive when the production justifies only *A* or *B*.

Obviously, if the drill guide hole, or holes, of a jig can be eliminated altogether, so that only the fixture features remain, a decided saving in tool costs can be realized. This is what was done on the job illustrated in Fig. 41. Arrangements were made in the die to spot each of the holes in the casting to start the drill, making bushings unnecessary. An attachment to a drill press, which serves the same purpose is described and illustrated in Fig. 230. The tool can be preset to locate a number of holes consecutively and accurately in a definite pattern for any number of a series of workpieces. Although the attachment is by itself much more expensive than almost any drill jig, it can be reset and used readily from one kind of part to another, whereas a drill jig usually is built for one particular part and, after production has ceased on that line, the jig is worthless. Where either a jig or the hole spacer can be used on a job, the direct time with either device is about the same, but the fixed charges in many cases are less for the hole spacer.

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[12] C. W. Hinman, *Die Engineering Layouts and Formulas*, p. 157. New York: McGraw-Hill Book Co., Inc., 1943.

As is pointed out in Chap. 14, accuracy is maintained over a longer period of time when harder but more expensive materials are used. Obviously, judgment must be exercised in the selection of wear-resistant materials to obtain the lowest fixed cost per unit produced.

In making tools, as with almost everything, there are a number of ways of turning out a suitable article. Ordinarily, the toolmaker is not in a position to know what the ultimate requirements are for a specific job nor can he be expected to be acquainted with all the considerations affecting the choice of a suitable type of construction. The tool engineer has the means of ascertaining the necessary features that a tool should possess but in addition must have an understanding of the toolmaking procedures available to satisfy the tool's requirements so that he can specify the most economical for the purpose. It is not possible within the framework of this text to give a complete treatment to the art of toolmaking nor describe many of its practices, but a few examples are offered to illustrate the necessity of an understanding of it as a basis for specifying economical tool construction.

Medium- or large-sized jig, fixture, and machine bodies may be cast in one piece or fabricated by welding from steel shapes. If a pattern must be made and charged against one casting, welded construction is cheaper and quicker, especially since the casting must be machined. A welded steel unit is stronger than a cast unit of the same weight and if strength is the only consideration, the choice of welding is indicated. To benefit from this choice to the utmost, a knowledge of the best ways of utilizing welding techniques is essential. For quantity production of tool bodies, casting is adaptable to production methods. Cast iron also has superior ability to dampen out vibrations and wearing properties for slides. For these advantages, castings may be the logical choice for certain tools. In such cases, an understanding of the proportions which save coring, allow the pattern to be drawn from the sand most easily, benefit the flow of the iron in the mold, insure uniform cooling, and result in the minimum of machining is helpful.

Castings for commercial products, which must appeal to the eye or for which functional strength is carefully calculated, may have generous fillets. These are placed on a wood pattern in the form of leather strips. A cheaper way is to make small wax fillets on a pattern. Such fillets may serve quite as well as larger ones for tool castings, where only one or a few are to be made. That is one example of how the cost of building tools may be kept down. Other examples are suggested in Figs. 117, 118, 125, 127, 128, and 130. Although they are shown as desirable features of product design, the ideas conveyed by those figures are applicable to toolmaking as well.

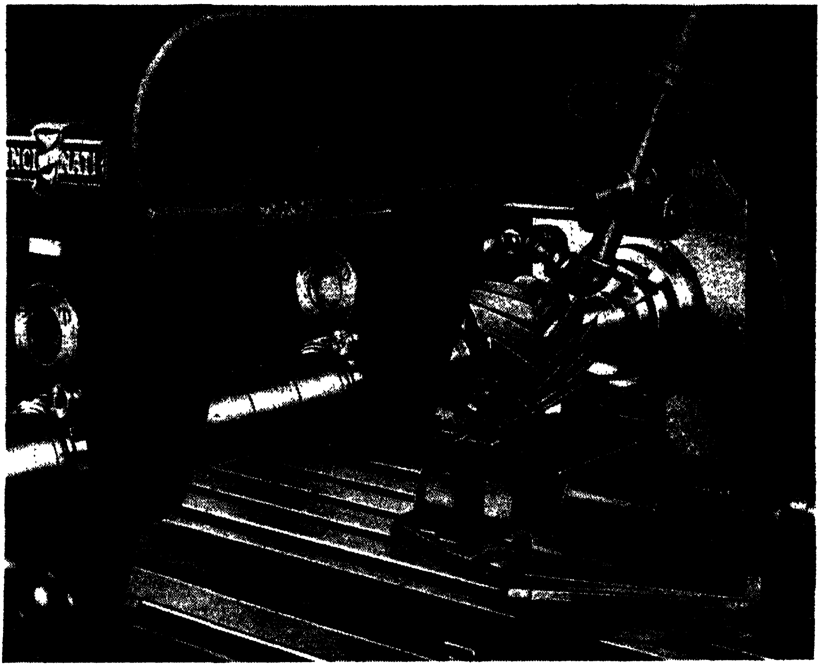


Fig. 61. A vise fixture. The standard plain vise on the milling-machine table is equipped with special jaws for holding the irregular workpiece that could not be held satisfactorily in the standard jaws. Special jaws can often be applied to a standard vise at a lower cost than a fixture can be made for a part. (Courtesy Cincinnati Milling Machine Co., Cincinnati.)

The jig borer depicted in Fig. 100 is an invaluable means of building accuracy into tools. Its effective use requires care and skill and an appreciation of techniques by which accuracy is obtained and of their capabilities and limitations is essential to get desired results at the least possible cost.

The cost of a tool which is usable for only one job must be charged entirely against that job. On the other hand, a tool which is adaptable to more than one job is logically carried by all, and its cost prorated over all the jobs is comparatively small for each. Consequently, economy can often be achieved by calling for fixtures, jigs, dies, etc., which are not confined to one application. This is carried out in a common practice of making special-shaped jaws to fit specific parts to be machined; the jaws being replaceable in standard vise bodies. An example of special jaws on a standard vise is shown in Fig. 61. A universal fixture body with special jaws, used on many jobs in one shop, is shown in Fig. 58. One of the advantages of commercial universal jig and fixture bodies, like those shown in Figs. 43, 44, and 198, is that usually only a few minor details need to be added to a suitable body to adapt it to a specific part. When that part is discontinued, the special details may be removed, and the body is salvaged. Often several sets of special details are stocked for a number of different parts which are run at intervals. Whenever it is desired to run one of the parts, the appropriate details are placed on the universal body.

The lamp bases shown in Fig. 62 must have three holes in some models, six in others. By punching these holes instead of coring them, one die suffices for all the castings. Thus by an arrangement that is well thought out, the cost of one die is saved.

Standard tool details are available in commercial form. Standard commercial machines, holding devices, cutting tools, gages, etc. are cheaper, more quickly obtainable, are based upon more comprehensive design effort, are produced in sufficient quantities to justify the most suitable equipment for their manufacture, and are subjected to much more extensive and severe testing than specially made tools and equipment. Therefore, if properly selected, they are more likely to possess desirable qualifications for any job for which they are adaptable and should be chosen whenever available and suitable.

A representative commercial tooling item is the universal jig and fixture body which is offered by a number of manufacturers in a

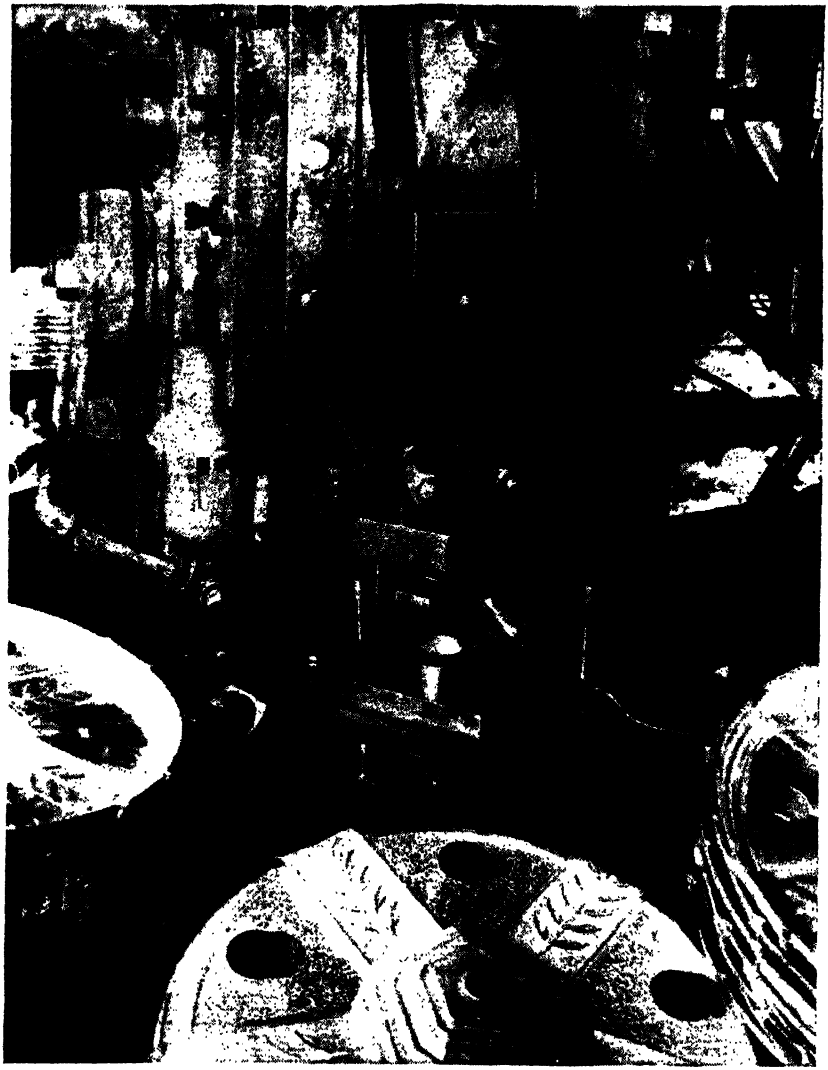


Fig. 62. Good design saves tooling. Several holes must be pierced in a thin section lamp base. Some bases must have three holes, others six as depicted. The castings are pivoted in the central hole, around a pin in front of the die, and indexed against a pin. The holes are about 1¼ in. in diameter and could be cored, but a punching operation would still be necessary to remove the flash. Also, two different casting dies would be required for the three-hole and six-hole models, if the holes were cored; whereas one die answers for both when the holes are pierced. (Courtesy New Jersey Zinc Co., New York.)

large variety of types and sizes. Jigs constructed from such universal bodies are illustrated in Figs. 43, 44, and 198. Usually, it is only necessary to add locators and bushings to an appropriate universal body to construct an efficient drill jig.

A widely used commercial accessory for punch press work is the die set. Figure 63 shows a punch and die constructed from a typical die set and standard punching units.

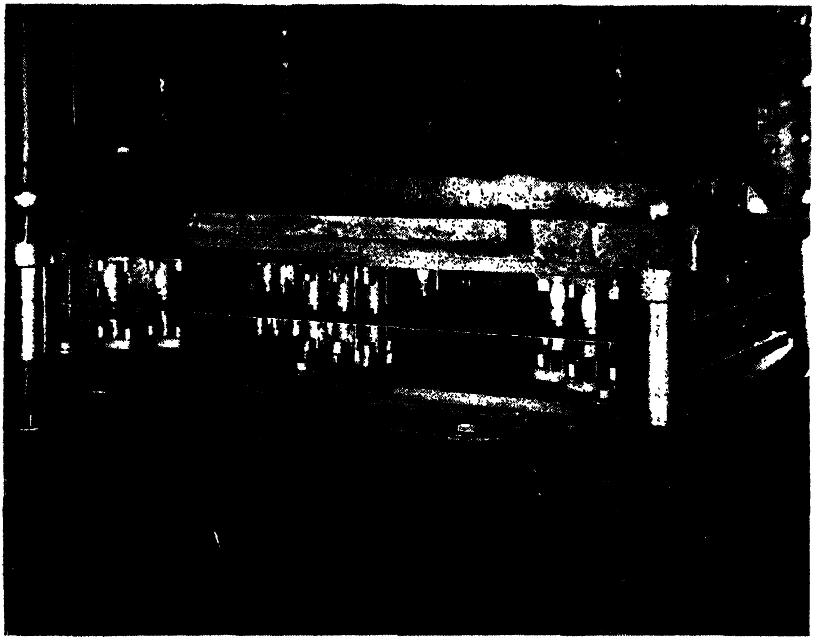


Fig. 63. Commercial die units. Commercial hole-punching units are mounted on a standard die set to make this die for punching a number of holes in a sheet of metal. The building of such a die becomes a simple assembly job. The components from which the die is constructed can be purchased much more cheaply than comparable special details can be custom-made, one or a few at a time, in the tool room of a manufacturing plant. (Courtesy Wales-Strippit Corp., North Tonawanda, N. Y.)

The list of standard commercial tools is large and continually growing. Included are cutters of many forms, types, and sizes, fixture cams and clamps, and gages. A view of representative jig and fixture details is presented in Fig. 64. The layout of a milling fixture for the most part made of standard details is Fig. 65. A standard type of collet fixture is shown in action in Fig. 20. Substantial savings in tool costs can be realized by contriving to use as many standard tools as can be substituted for special ones.

Standard machine units are the major components of machine tools intended for general purpose or conventional production jobs. Drill presses, radial drills, knee- and column-type milling machines, and production-type milling machines are a few among this class. They are made in quantities at a much lower cost than machines can be made individually. Design cost, pattern costs, setup and equipment charges incurred in their manufacture can be allocated over many items. Their parts, made in lots by specialists, have a comparatively low unit cost. But because standard machines must be versatile to appeal to a wide market and enjoy large sales, they

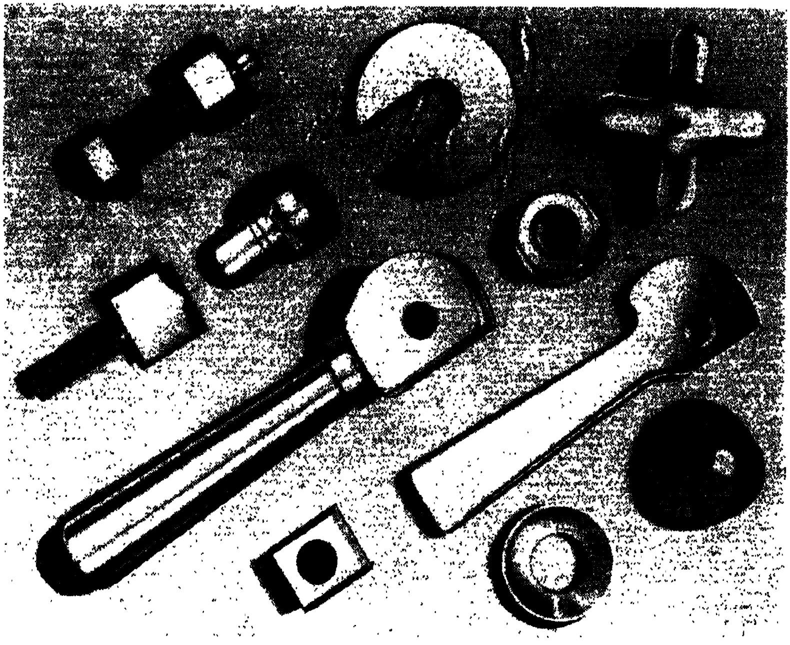
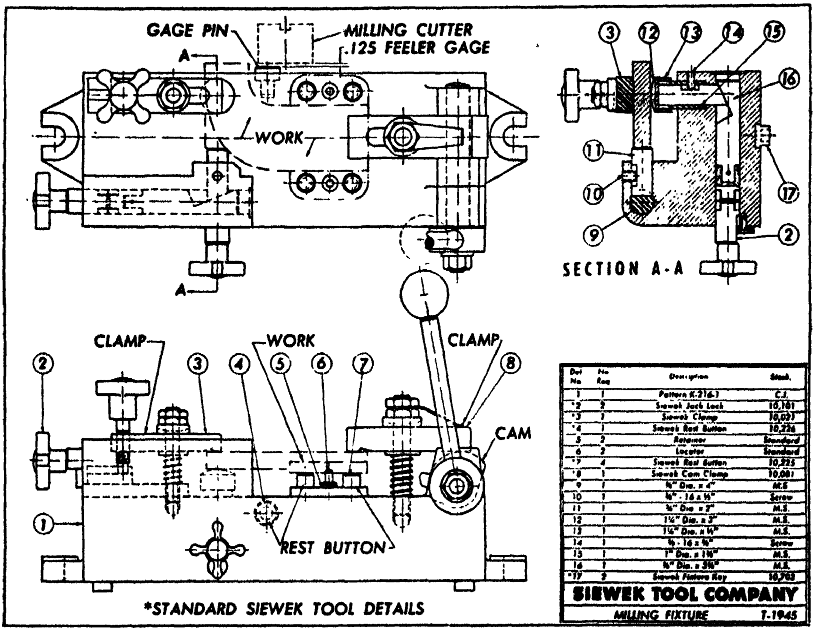


Fig. 64. Standard commercial jig and fixture details. Many such commercial items are available in a large variety of shapes and sizes. (Courtesy Siewek Tool Co., Detroit.)

are not as efficient for many jobs as are special machines directed to doing specific tasks rapidly and easily.

All machine tools, whether standard or special, perform specific types of functions, such as drilling, turning, and milling. No matter what the approach or manner of doing a particular type of function, certain basic equipment is needed for it. Thus, whether drilling is done on a simple drill press or on a complex automatic machine, a spindle revolving in a drill head is necessary. This provides the basis for a principle important from the standpoint of economy in special machine tool construction. The principle is that of *unit construction*, whereby units (major components) of standard machines are arranged in a desirable manner and combined with supplementary adjuncts to make a special machine tool. This practice has contributed markedly to reducing the extent and hazard of the investment required for special machinery.



Det No	No Req	Description	Stand.
1	1	Pattern K-216-1	C.I.
*2	2	Siewek Jack Lock	10,101
*3	1	Siewek Clamp	10,021
*4	1	Siewek Rest Button	10,226
5	2	Retainer	Standard
6	2	Locator	Standard
*7	4	Siewek Rest Button	10,225
*8	1	Siewek Cam Clamp	10,081
9	1	⅝" Dia. x 4"	M.S.
10	1	⅜"-16 x ½"	Screw
11	1	⅜" Dia. x 2"	M.S.
12	1	1¼" Dia. x 3"	M.S.
13	1	1½" Dia. x ¼"	M.S.
14	1	⅜-16 x ⅝"	Screw
15	1	1" Dia. x 1⅜"	M.S.
16	1	⅝" Dia. x 3⅜"	M.S.
*17	2	Siewek Fixture Key	10,703

SIEWEK TOOL COMPANY

MILLING FIXTURE T-1945

Fig. 65. A layout drawing of a milling fixture using standard details. (Courtesy Siewek Tool Co., Detroit.)

A simple, inexpensive, but highly productive, machine made of standard drill press units is shown in Fig. 66. A standard drill press column has two heads in opposition and held horizontally. Inserted blade cutters and a special work holding fixture complete the assembly.

Figure 67 shows two drill head units of standard construction that are made in quantities specifically for use in various special arrangements. Such heads come in various sizes and for light or

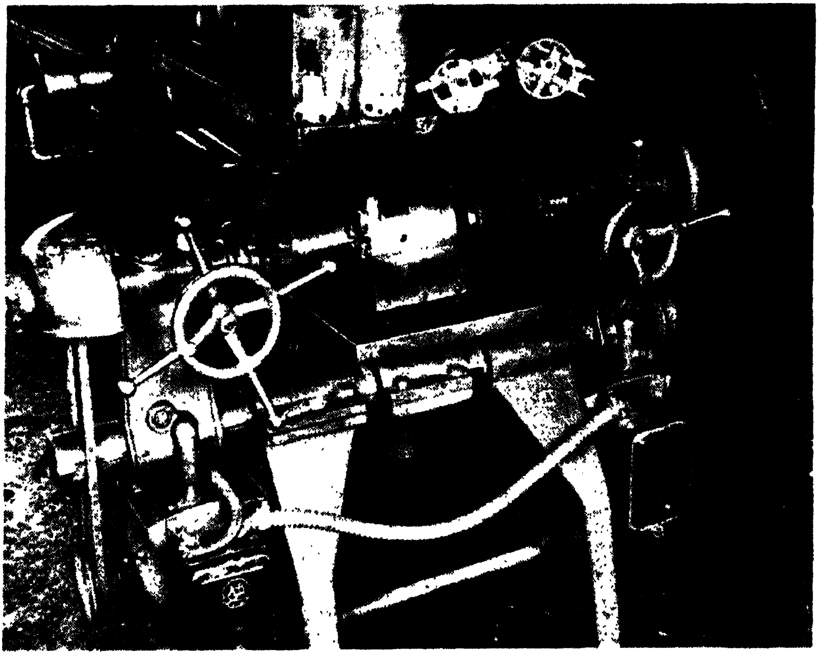


Fig. 66. An inexpensive special machine made of standard units. This is a machine constructed for the specific task of facing the ends of die cast aluminum motor housings, the same part as shown in Fig. 59. The machine is made of recognizable units from a common type of sensitive drill press combined with several special items. The press column is held horizontally on legs, and two heads are mounted on the column with their spindles in horizontal opposed positions. Each spindle carries an inserted blade cutter. A special fixture for the workpieces is mounted between the heads. Handwheels are used to advance the spindles and tools for light cuts, the depths being limited by the conventional stops. Both ends of seven hundred castings an hour are faced. (Courtesy New Jersey Zinc Co., New York.)

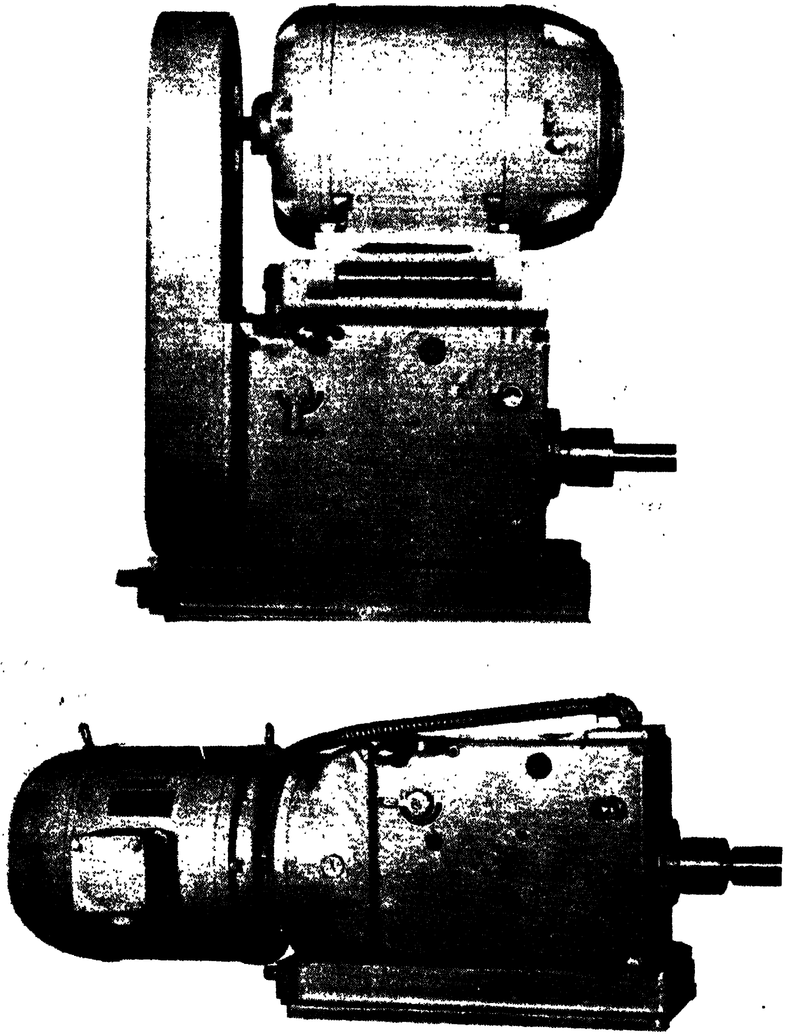


Fig. 67. Two basic drill head units of standard design. One has a gear drive, the other a belt drive. Such heads come in various sizes and for light or heavy duty. A built-in cam feed causes the head to move on its base or column with rapid approach, feed, dwell, and return through a predetermined cycle. Attachments are available for increasing the versatility of these heads. They include a feed reducer, bushing carrier that pilots on to the fixture to align tools, multispindle auxiliary head for operations of similar size and depth, and controls to start the cycle and interlock with an index table.

heavy duty. Figure 68 illustrates two typical applications of standard drill head units and indexing bases with special mountings for the heads and special work holding fixtures and jigs arranged for specific jobs. Had custom-built units been used throughout these machines, their cost no doubt would have been considerably higher. Ordinarily, one machine of this type operates on only one part, although occasionally one machine can be arranged to perform similar operations on similar parts with only minor changes. In any event, production must be high for the machine to be economical.

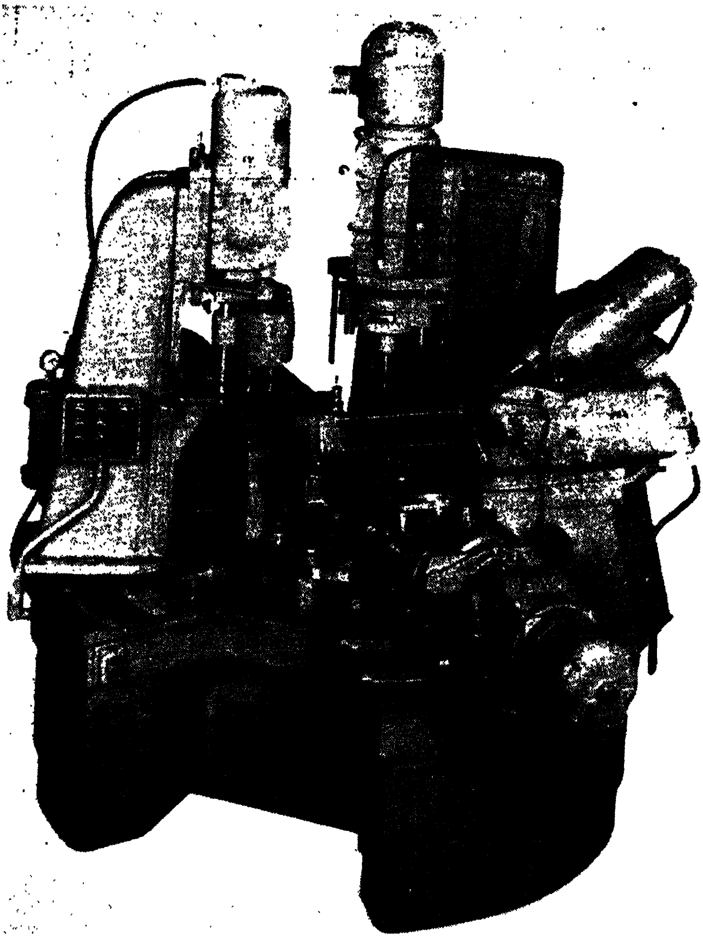
Figure 69 shows the principal components of a manufacturing-type milling machine. Cuts on this type of machine are confined to one or a few planes. If other passes are required they must be performed separately or combined on a special milling machine. If production is high enough, it may be profitable to take a number of cuts at the same time to save separate operations. The initial cost of the special milling machine for this kind of service can be minimized by an arrangement of standard units plus a few additional special components.

Figure 70 is an example of a milling machine built basically from standard units arranged to do a specific job in an efficient manner. The base, table, hydraulic feed unit, drive, spindle carriers, and quills are components of a conventional manufacturing-type milling machine. The addition of the special column and horizontal arm, drive extension, and the fixtures for holding the workpiece has provided for the particular adaptation.

The apparently elaborate construction of Fig. 71 is not in reality much different from the usual duplex manufacturing-type milling machine, to which has been added a bridge rail on top of the columns and a drive extension to a third standard spindle carrier placed in a vertical position.

The milling machine shown at *A* in Fig. 72 was originally built with four special close-coupled spindle carriers for the machining of steering knuckle lugs. When that job was discontinued, it was not necessary to scrap the assembly completely as often is the case with entirely special machine tools. Instead, it was altered to the form shown at *B*, Fig. 72, saving the bed, table, one column, and drive

Used singly or in units with suitable base and fixtures, heads like these provide the nucleus for a multitude of special-purpose machines of not excessive cost. Examples of machines constructed in this manner are shown in Fig. 68. (Courtesy Kingsbury Machine Tool Corp., Keene, N.H.)



(A)

Fig. 68. Special machines made of standard units. In view (A) is a 13-spindle, 26-in. automatic indexing machine for drilling, reaming, and tapping the rear servo body in an automobile transmission at the rate of 155 pieces an hour. The main heads have auxiliary multiple-spindle heads attached.

View (B) shows a 26-in. automatic indexing machine for drilling three holes in mineralite bowling balls at the rate of 240 balls per hour. The operator can adjust the position of each unit within limits to change the relative position of the three holes, to suit hands of different sizes. The heads are equipped with bushing carriers to guide drills.

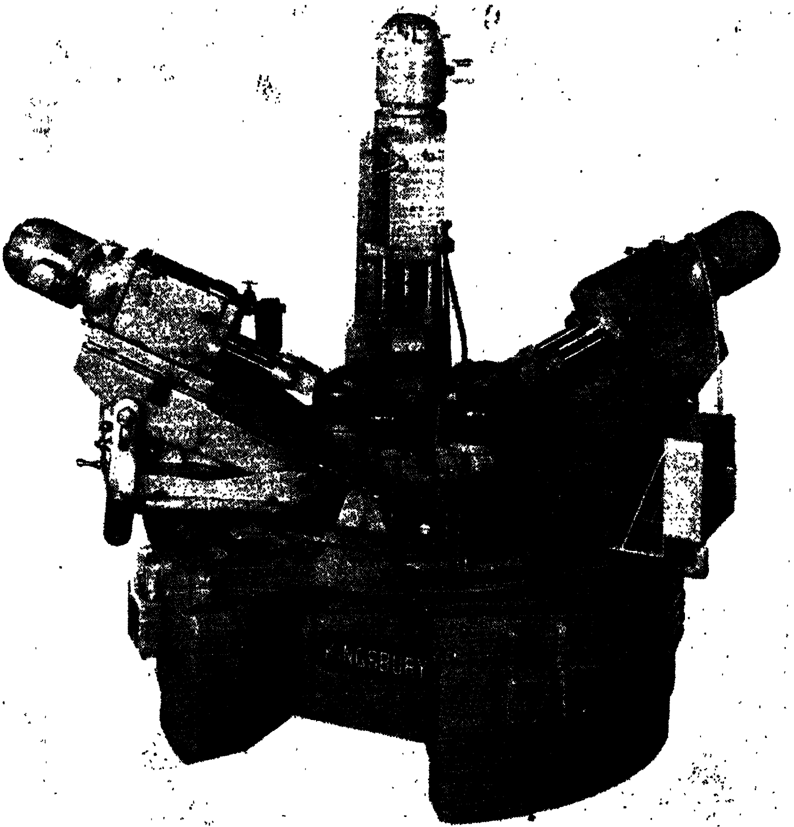
These machines utilize standard drill head units like those described in Fig. 67, arranged on a standard index base with special mountings for the heads and work holding fixtures. (Courtesy Kingsbury Machine Tool Corp., Keene, N.H.)

unit. Among the units added for the revision were a standard spindle carrier and quill, at right, available at a much lower cost than a comparable custom-made unit.

SUMMARY

The aim of economy in tooling is to secure the lowest unit cost. This means that direct, indirect, and fixed costs must all be considered.

Direct costs are incurred in the elements of an operation. Some elements reflect the motions and exertion of the operator; others,



(B)

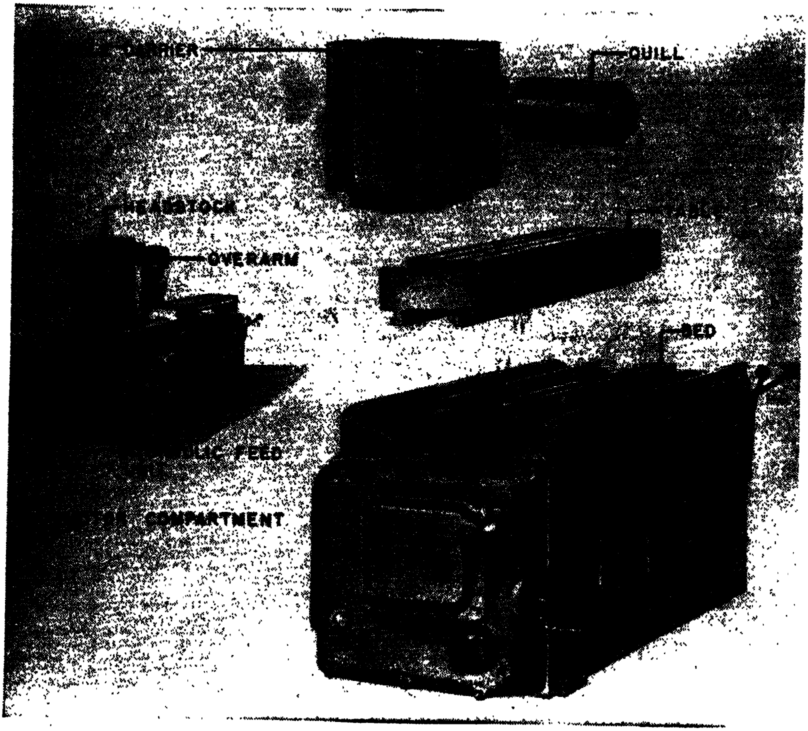


Fig. 69. The main elements or units of a typical hydraulically fed manufacturing-type milling machine. In this type of machine versatility is sacrificed for ruggedness, the capacity to remove metal rapidly, and simple and rapid manipulation. Cutting feed is available in only one co-ordinate direction, and although adjustments are possible between cutter and work in the other two directions of space, they are time-consuming. Table movement can be set for a variety of cycles, but for only one at a time. Movement is started through a cycle by the twist of one lever and is stopped automatically.

Parts machined on a manufacturing-type milling machine usually must be held in a special fixture to bring them into proper relationship to the cutters. Thus, production quantities must be sufficiently large to warrant the construction of the fixtures and use of this type of machine. Even so, milling is limited on the standard models to one or a few planes, and if other passes are required, adaptations similar to those illustrated in Figs. 70, 71, and 72 may be necessary or desirable. (Courtesy Cincinnati Milling Machine Co., Cincinnati.)

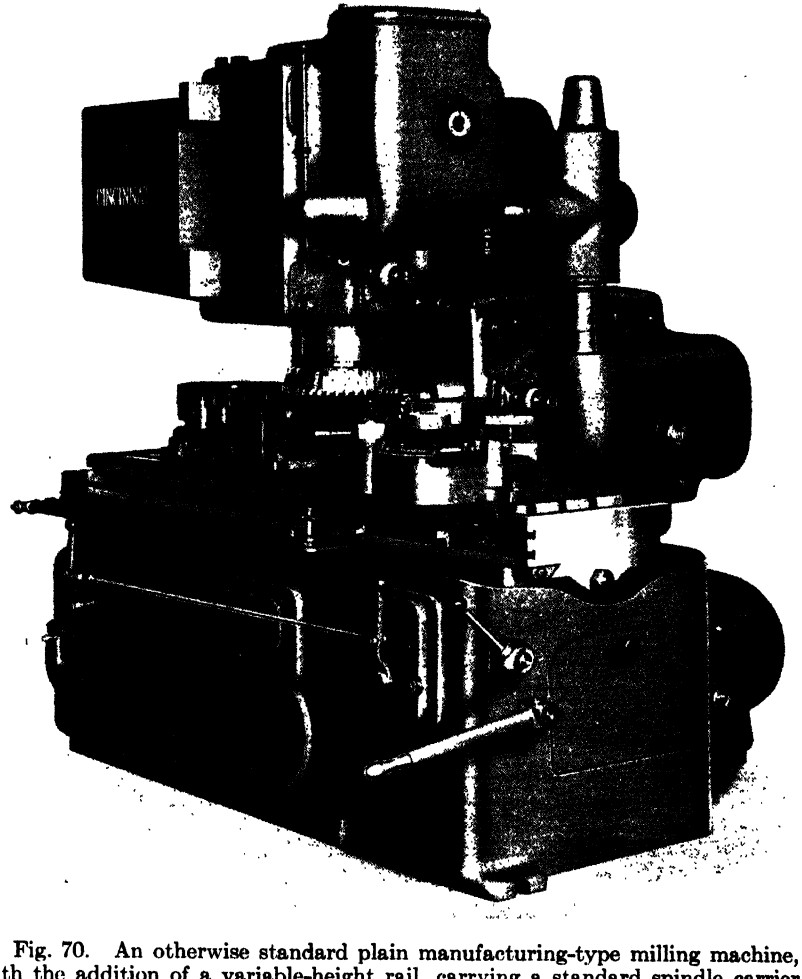


Fig. 70. An otherwise standard plain manufacturing-type milling machine, with the addition of a variable-height rail, carrying a standard spindle carrier mounted vertically for milling the flange face, bottom and side pads of a tractor crankcase front cover. With fixtures at both ends of table, a reciprocating table-feed cycle is employed. (Courtesy Cincinnati Milling Machine Co., Cincinnati.)

the machine activity. Direct costs can be reduced by reducing elements, eliminating elements, or combining elements. To this end, use is made of the principles of:

1. Motion economy applicable to machines and tools, to:
   a. Eliminate unnecessary movements.

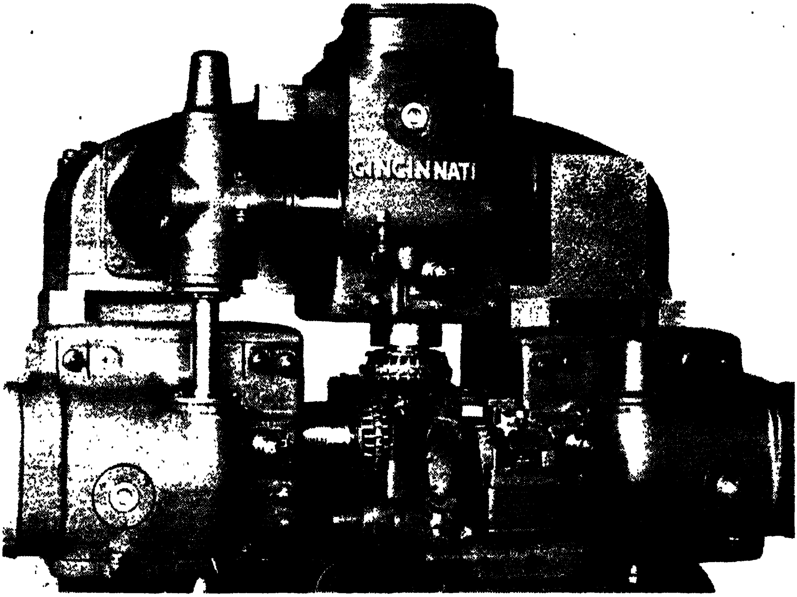
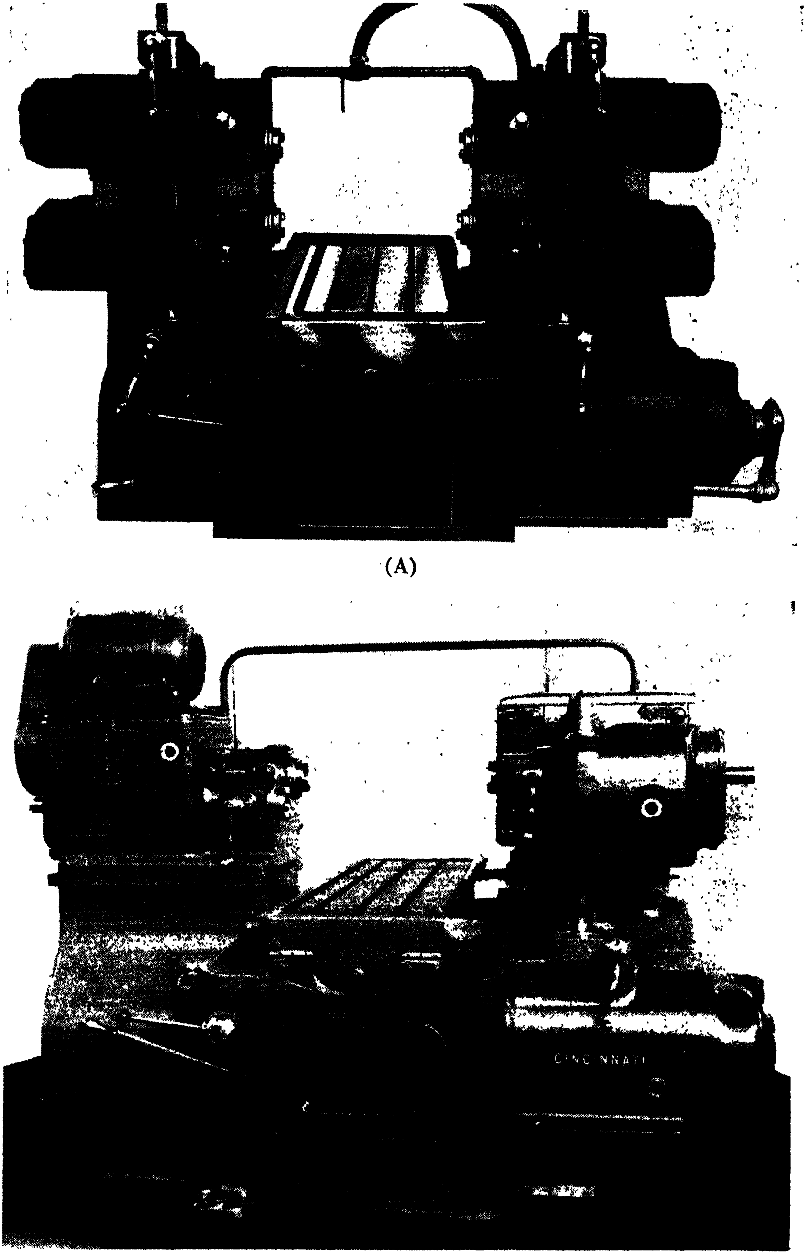


Fig. 71. A special milling machine constructed of standard units. By the addition of a special bridge-type fixed-height rail and a third standard spindle carrier to an otherwise standard duplex production milling machine, means are provided for milling the top, as well as the sides of cast-iron meter bodies in one operation, with a comparatively small investment in special equipment. (Courtesy Cincinnati Milling Machine Co., Cincinnati.)

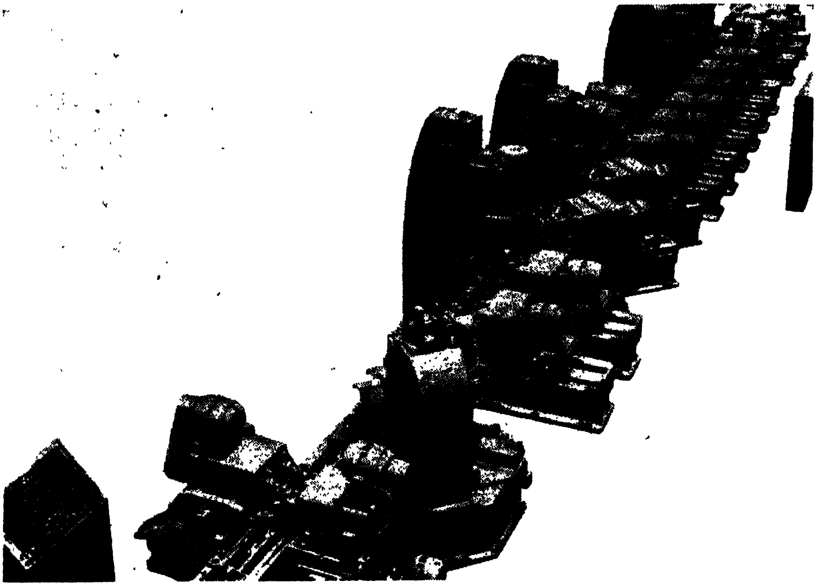
Fig. 72. How standard units may be salvaged. The machine at *A* was originally used for straddle-milling brake-hanger lugs on steering knuckles. It was built up of standard bed, table, drive, and column units with four special spindle carriers. After the original job was discontinued, the machine was rebuilt and rearranged, as shown at *B*, for milling both ends of cylinder blocks. The standard bed, table, drive, and one column were salvaged and re-used. A standard spindle carrier and special column and spindle unit (on the left) were all that had to be added. Unit construction permitted the change over with a minimum expenditure. (Courtesy of Cincinnati Milling Machine Co., Cincinnati.) [Opposite page]



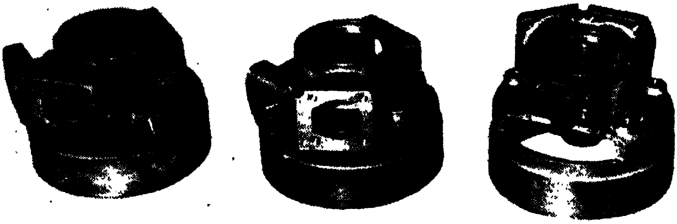
(A)

(B)

[Fig. 72]



(A)



(B)

Fig. 73. View (A) shows a 24-station transfer machine, which does most of the machining required on cast-iron compressor bodies for a leading line of domestic refrigerators. This is an example of a modern trend in production-machinery design, where large quantities of identical pieces are required.

The left view in (B) shows the rough casting with preliminary machining as it comes to the transfer machine. The pieces are located in pairs on fixtures that are carried from station to station, and automatically positioned for the various cuts. On each pair of compressor bodies, 152 separate operations are performed as they go through 19 working stations, 2 inspection stations, 1 loading station, and 2 idle stations. These operations require 50 drills, 12 face mills, 2 side mills, 2 end mills, 12 boring tools, 38 chamfering tools, and 36 taps.

All of the 31 operating units are fully automatic, hydraulically operated, and electrically interlocked. The master control panel is shown at the beginning of the line. Each station is a twin unit, working on two pieces at once. Not shown

  - b. Shorten and simplify necessary movements.
  - c. Balance the work.
  - d. Minimize the use of the eyes.
  - e. Eliminate use of hands for holding.
- 2. The prevention of undue strain and fatigue by:
  - a. Providing comfortable working conditions.
  - b. Conforming to physiological traits.
- 3. Alleviation of heavy manual labor by:
  - a. The transfer of power to relieve manual effort.
  - b. Lightening of direct burden.
- 4. The conservation of skill by:
  - a. The transfer of skill.
  - b. Improving the advantage of perception.
- 5. Combining operations through:
  - a. Simultation.
  - b. Integration of cuts.

Indirect costs are incurred from the services that are vital to the smooth continuance of production. Some of these costs are dependent, at least partially, upon tooling, and may be minimized by:

- 6. Reducing the cost of auxiliary functions such as:
  - a. Inspection
  - b. Scrap disposal
  - c. Setup and change over
  - d. Cleaning
  - e. Maintenance, upkeep, and repairs.
- 7. The promotion of safety. Unsafe conditions result in real costs. Tooling may be applied to:
  - a. Safeguarding the working zone.
  - b. The safety of controls and mechanisms.
  - c. Protection against moving parts.

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in the picture are a power-driven return conveyer for the work-holding fixtures, and a power-driven chip conveyer underneath the full length of the machine.

The second and third views of the piece show it after it comes off the transfer machine and illustrate the variety of work performed from three side directions and above. Only two operations remain to finish the piece—diamond boring the cylinder and main bearing and grinding or lapping the cylinder head contact face. The machine produces 188 pieces per hour at 88% efficiency.

This type of machine embodies many of the principles of tooling for economy. Similar machines have been made and are used for a large variety of products. (Courtesy Greenlee Bros. & Co., Rockford, Ill.)

8. Co-ordination with movement of materials, to reduce handling costs, promote a smooth flow, and avoid workpiece mutilation.
9. Considering availability to save costs of delays.

Low fixed costs can be had from low initial expenditures for equipment, providing functional ability is not sacrificed. This means:

10. Low construction costs, realizable from:
    a. Observance of the principles of economical construction.
    b. The use of standard tool details.
    c. The adaptation of standard machine units.

QUESTIONS

1. With what classes of costs are process and tool planning concerned?

2. How may an operation be analyzed to find the least time to do it?

3. What are the five principles of motion economy of most concern to the tool engineer?

4. To what elements of an operation do the principles of motion economy apply? Why?

5. The principles upon which the use of tools are based point to what economies?

6. Describe eight principles underlying methods of achieving economy in processes and tools.

7. What rules are helpful guides to eliminating unnecessary movements? Illustrate each by an example.

8. What movements may be substituted for hand movements? Does the replacement always need to be complex?

9. How may motions for disposing of a workpiece from an operation be reduced or eliminated?

10. How may movements sometimes needed for positioning an object be reduced or eliminated?

11. What rules apply to shortening and simplifying necessary movements?

12. In what ways may a working area be arranged to shorten and simplify motions?

13. What can be done with loose tools to cut down motions?

14. How can the motions for cleaning locating surfaces and clearing away chips be kept at a minimum?

15. What constitutes a "barrier" in an operation and what effect does it have?

16. How may a cutting fluid aid in reducing motions?

17. What rules apply to balancing work between the hands?

18. Describe arrangements for keeping both hands of a machine operator busy.

19. How can the use of the eyes be minimized?

20. What effect may the sizes of levers or buttons have upon the ease with which an operation may be performed?

21. Why are eye movements important in an operation?

22. What kind of a holding device is the human hand?

23. What kind of a lever on a machine tool is never locked in "go" position?

24. In what two general ways may the effects of strain and fatigue be relieved?

25. What can be done to provide comfortable working conditions?

26. What should be the workplace height when an operator is seated? When he is standing?

27. What provisions can be made to permit an operator getting close to the working area?

28. What are some of the ways in which a designer can cater to physiological traits of human operators?

29. Why are duplicate pedals or controls advantageous?

30. What form of handles for tools and cranks are most efficient?

31. Where should levers and controls be placed? Why?

32. How may heavy manual labor be alleviated?

33. What are some of the devices by which the principle of the transfer of power is applied?

34. What three advantages do air or hydraulic clamping have over manual clamping?

35. What may be done to lighten jigs?

36. How can skill be conserved?

37. In what ways can skill be transferred to tools and machines? Give an example of each.

38. What relation does the perception of a job have to the skill required to do it?

39. How may operations or elements be combined?

40. What is meant by simultation? Describe examples of it.

41. What advantage is to be gained from integrating the cuts made on a part?

42. What are some of the auxiliary services for which the tool engineer can furnish equipment to reduce costs?

43. In what two ways may benefits be derived from furnishing gages at the workplace? Give an example.

44. What consideration should be given to scrap disposal for economy?

45. What economies are justified for se up and change over?

46. How can the cost of maintenance, upkeep, and repair of equipment be kept down?

47. To what degree should long life be built into a tool?

48. How are tools made so that they can be repaired easily?

49. How does the use of standard commercial details for tools help repairs?

50. Why is safety an important economic consideration?

51. What three kinds of protection can the tool engineer furnish in safety equipment?

52. What is meant by "protection of the working zone"? Give an example of it.

53. Classify protective arrangements which may be adapted to operations where the pieces are fed individually.

54. Describe the following safety devices: (a) dial feed, (b) chute feed, (c) interlocking gate guard, (d) sweep guard, (e) electronic guard, (f) pull out, (g) two hand trip.

55. Why are not many machines made fully automatic?

56. Give several examples of precautions for the safety of controls and mechanisms.

57. How may tooling serve to co-ordinate operations with the flow of materials?

58. In what three general ways can economy be realized in machine and tool construction?

59. State four principles of economical construction of tools.

60. How elaborate or complicated should a tool be?

61. How much quality should be built into jigs and fixtures? Give an example.

62. Why are standard universal fixtures and jigs economical?

63. Why are standard tool details often superior to special details?

64. What advantages are offered by standard machine units for the construction of special machine tools?

65. What characteristics make it possible to use standard machine details in the construction of special machine tools?

66. What principles of tooling for economy are embodied in the transfer machine of Fig. 73? Describe how each principle is utilized.

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5 PRINCIPLES OF ESTIMATING

THE NATURE OF ESTIMATING

Why cost estimates are needed

The economy of one machine or tool as compared with another, the most economical method for a job, the advisability of replacing a piece of equipment, or the return that can be expected from a proposed investment can be ascertained from comparisons of costs. An important part of any such problem is the estimating of the costs.

One of the frequent duties of a tool engineer is to furnish management with comparative estimates of the cost of manufacturing an article. Studies of that sort involve an appraisal of the costs of designing and making tools and equipment, of purchasing standard machines and tools, and of the labor and overhead necessary to produce the parts.

It is not uncommon for the selling price of a manufactured article to be set, at least in the beginning, by the estimated cost. In fact, the cost estimates often determine whether or not a product is actually made. Much business is contracted on the basis of its probable cost of manufacture. Estimates of cost must be reasonably accurate if a venture is to be successful. If a job is overpriced, it is lost to a competitor. If it is underestimated, it results in a financial loss.

The tool engineer's function is not only to furnish the machines, tools, and equipment to do a job, but also to provide these means of getting it done at the lowest possible cost. To assure this end, he must plan all contingencies with the least possible chance of error. The ability to foretell costs with reasonable accuracy is the keystone of effective planning, for it is the cost that determines ultimately whether the project will succeed or fail. Estimates are frequently used to control expenditures during manufacture by holding them to the amount originally requested.

What an estimator does

In large organizations certain members, called estimators, specialize in the preparation of cost estimates. Whether they devote their full time to the subject or depend upon it to reinforce their over-all activity, as do the tool engineers, they must possess certain qualifications for a competent grasp of the endeavor. An estimator must know where to find specifications of common materials; be able to visualize and outline all the necessary steps to manufacture an article; draw upon sufficient knowledge of cost accounting to be able to read and take full advantage of cost records; understand the fundamentals of time and motion study and be able to prepare and make use of standard data from that source; designate the proper tooling for a job; and evaluate alternate methods of operation. To the uninitiated the degree of accuracy to which an estimator can attain is often amazing. In one large machine tool plant, engineers estimate and quote on special equipment and tools for the concern's customers. The estimated and actual costs respectively of each engineer's assignments are totaled semi-annually and the two are expected to agree within 10 per cent. Most engineers and estimators experienced in a field can point to records equally as good and frequently better.

Fundamentals of estimating

An estimate has been defined as a guess based upon all known measurable factors. Any attempt at foretelling events must be based upon what experience has shown to have happened under comparable circumstances in the past. Thus, the problem of estimating future performance is to determine what must transpire and what the resulting charges will be.

There are many individual variations of estimating procedure. Some men draw heavily upon extensive experience and retentive memories. Others are more methodical in their use of recorded information, in the forms of tables and charts. Fundamentally, however, all operate on the basis of one general principle. That is to divide a job into parts that can be evaluated by either calculations or comparison with identical past performance. The extent to which a task is divided depends upon the form in which usable and comparable information is available.

Over-all comparisons

Previous estimates or actual cost records sometimes reveal data on similar parts or operations that can be adapted wholly to a case at hand. Care must be exercised to ascertain that the figures used reflect sufficiently identical conditions to warrant their full application. For instance, for a previous operation, makeshift jigs, fixtures, or tools for a few parts may have caused a larger labor cost than is justified on a current run where the quantity is sufficient to justify special tools and equipment for the job. Also, past records may have been based upon economic conditions for which labor and overhead rates were different from those in existence for the present occasion. Available equipment or its arrangement may be entirely different under present circumstances from what it was in the past for which records are at hand.

Comparison of elements

Often estimates based upon over-all comparison with similar projects are inadequate or unobtainable. Resort must then be made to dividing each operation into elements and comparing them with those from a number of other jobs. Any manufacturing operation is composed of a series of basic elements, each of which is part of many other operations. Elements from many jobs are measured and tabulated. Suitable elements for the job under consideration are selected from the tables, and their time values are added for an estimate of the total time needed for the task.

THE ITEMS OF COST

Breakdown by functions

The manufacture of an article requires a number of distinct contributions, which may be designated in the following manner:

1. Auxiliary services.
    a. Designing and drafting.
    b. Production planning and drafting.
    c. Procurement or fabrication of special patterns, core boxes, flasks, or tools.
    d. Experimentation, development, testing, or runoff.

2. Fabrication functions.
   a. Casting, forming, machining, or finishing processes.
   b. Assembly.
   c. Painting, packing, etc.

Consideration for estimating is usually given separately to each function because of the differences in the problems encountered.

The basic costs of production

Fabrication functions normally incur two kinds of costs, direct and indirect. Direct costs include those for material and labor. Direct material cost includes that for all materials which can be conveniently measured and associated directly with the article produced. Direct labor cost includes that for all productive labor which can be conveniently measured and associated directly with the specific productive function. That includes preparatory work like setup.

Indirect cost or overhead for estimating includes supervision, light, heat power, space charges, etc. It also takes in those charges which were referred to for the purposes of economic comparisons as fixed charges, such as depreciation, interest, taxes, and insurance. Incidental direct costs like power and maintenance are usually thrown into overhead. Some auxiliary functions, like production planning, may be included in the overhead of production instead of being treated separately. The commonest method of distributing overhead for estimating purposes is the direct labor dollar method. Other ways, like the direct labor hour rate and the machine hour rate, may be used sometimes.

In most plants, the overhead or burden rate is determined by the cost-accounting department, which furnishes the figures to the estimator. It can be expected to be changed from time to time, as conditions in the plant change. The burden rate within a plant is often different from department to department. Obviously, an assembly department with little equipment should not have to carry as heavy a burden as a machining department, having heavy and costly machinery. Consequently, direct costs for making an article may be kept separate for the various departments in which work is done, so that the different overhead rates may be assigned to their proper direct costs.

The principal items of an estimate

A summary of an estimate must include the items that allow for the functions to be performed and their necessary costs. Thus, a typical list of costs for a manufactured article is: (1) engineering, (2) tools, (3) runoff and testing, (4) material, (5) direct labor, (6) burden.

All estimates do not need to take into account all of these items. Some may have another arrangement. The initial work on any estimate must be directed to finding a reasonable figure for each item that must be included.

The foundry production estimate sheet of Fig. 85 has a long list of items on its summary sheet. There the direct labor cost is broken down by departments, on lines 1, 3, 5, and 7, because the overhead rate varies among the departments, as shown by lines 2, 4, 6, and 8. The items of lines 9 and 10 may be considered auxiliary services. "Metal" on line 14 is material.

The tool estimate sheet of Fig. 86 is designed for tools as the end products. For that purpose, the summary on the lower right-hand section of the sheet includes engineering, material, labor, and burden.

In the following sections, the ways of determining the costs of the basic items will be explained.

ESTIMATING AUXILIARY SERVICES

Estimating direct time

A cardinal principle of modern manufacturing dictates that all possible mental work for the production effort be done beforehand and by specialists. To the extent that such contributions are original and creative, they are difficult to systematize and, therefore, not easily broken up into elements. For instance, it is not practicable to try to standardize the exact procedure an engineer follows in designing a machine. It is possible, however, to estimate fairly closely how long the engineer will take to complete the project from an over-all comparison with previous performance on a similar job. Thus, estimating the direct time required for an auxiliary service involves judgment in selecting comparable past performance and, from it, appraising the probable effort required for a proposed task.

Specific functions

The service designated as designing and drafting includes preparation of preliminary proposed sketches, specifications, bills of materials, orders, models, and mock-ups. Preliminary engineering is often done for jobs for which sales orders are never received. This cost must be charged to the jobs for which orders are received.

Production planning and scheduling includes also tool planning and designing, time and rate setting, estimating, and material scheduling. For continuous output, the cost of these services is normally a part of overhead. Only for special orders of sizable amounts which require considerable special attention is planning considered as a separate and distinct cost item.

The cost of jigs, fixtures, patterns, dies, and other tools may be considered only as an item in the total cost of a manufactured article, and thus may only appear in the list of costs to make that article. But when the cost of tools is to be estimated, they are looked upon as the products of the toolroom or tool shop. For that purpose, their cost is estimated in the same way as for any product by finding and totalling the indirect and direct charges that are incurred in making the tools.

Considerable time must often be spent in experimental work with new products or tools. Even with some tools of proved types, development is necessary to secure proper results. All contingencies cannot be foreseen in the original design. Forming dies, for instance, must almost always be modified by the diemaker and the proper die form developed after assembly to secure the exact results desired. All forms of jigs, fixtures, dies, and machine tools must be run off to prove their adequacy, and it is often found that changes must be made to correct imperfections. Such trials and tests are difficult to standardize, and judgment on the part of the estimator is often the only means of ascertaining beforehand the necessity and amount of effort required. Some labor is usually always needed, but in addition, allowances may have to be made for equipment, materials, and special technicians.

The cost of an auxiliary service is found by multiplying the estimated direct time for it by a rate to cover its entire cost. Some parts of an auxiliary service, like drafting, can be estimated for a job; but others, like supervision, are difficult to distribute. These latter should not be added as a burden to the direct time, which is already an indirect expense. A burden should not be piled upon a burden but should be included in the total rate for the service.

EXAMPLE 10: For a job the designing and drafting time is estimated to be 42 hours. The rate in the engineering department is $2.25 per hour. This rate is greater than the direct labor cost of the engineer or draftsman who carries through the job. It includes allocations for supervision, space, etc. Thus, the engineering charge for the job is

$$42 \times \$2.25 = \$94.50.$$

ESTIMATING MATERIAL COST

Relative value of material

The relative proportion of the material cost to the total cost varies with different types of jobs. Material may represent an almost negligible part of the total cost of light special equipment, where labor is preponderant. In quantity manufacture, material is a major item. Labor-saving methods tend to increase the ratio of material cost to the total. For normal manufacturing enterprises, material costs range[1] from 30 to 50 per cent as compared with direct labor cost of 20 to 30 per cent.

What material cost includes

An estimate of material cost must include not only the material found in the finished article but also that consumed in scrap, waste, and spoilage. Excess material is lost in chips, spoiled pieces, droppings, short ends, etc. Very little or nothing is ever realized from salvaged scrap. J. K. Olsen[2] found that scrap loss need not exceed 5 per cent. The quantity of raw stock purchased often is determined by the original estimate. A too liberal forecast may cause overbuying, with higher than necessary costs, and on the other hand an incomplete estimate may result in shortages. The manner in which material costs are estimated varies with the form of the raw material.

Many materials are priced by weight. Convenient tables are available in handbooks and catalogues specifying the unit weights, in pounds per foot or pounds per inch of common shapes, sizes, and forms of metals and other materials.

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[1] L. P. Alford and J. R. Bangs, *Production Handbook*, page 1047. New York: The Ronald Press Co., 1947.

[2] *Ibid.*

On a weight basis, the number of estimated pounds (or tons) are multiplied by the price per pound (or ton) for the total material cost. Judgment must be exercised as to validity of available price quotations in view of future market conditions, particularly if purchases are to be extended over a period of time.

In the case of bar stock to be machined, an addition must be made to the length of the finished piece for the stock consumed by the cutoff and facing tools. If the latter is anticipated, 1/32 to 1/16 in. per piece is usually adequate. The amount used for cutoff is equivalent to the width of the tool as determined by its strength and service requirements. Tough materials demand a wider tool than soft ones. The deeper the cut, the wider must be the tool. Table 2 describes practice which has been applied to the determination of the widths of cutoff tools for steel.

TABLE 2

CUTOFF TOOL WIDTHS FOR STEEL

Depth of Cut in Inches	Width of Cutoff Tool in Inches
Up to 5/8	5/32
1/2 to 3/4	3/16
5/8 to 1	1/4
3/4 to 1 1/4	5/16
Above 1 1/4	Usually 5/16

NOTE: Overlap provided for requirements of different grades and heat treatment of steels.

In addition, when bar stock is machined on turret lathes or automatic screw machines, some of it can be expected to be spoiled unavoidably during setup.

EXAMPLE 11: Estimate the cost of the material, hot-rolled steel at 11 cents per pound, to make 10 of the studs of Fig. 74.

The depth of cutoff is 5/8 in. below the chamfer, so from Table 2 a cutoff tool 3/16 in. wide will probably be needed. No allowance in this case is made for facing end. The total length per piece is:

$$2\tfrac{11}{16} + \tfrac{3}{16} = 2\tfrac{7}{8} \text{ in.}$$

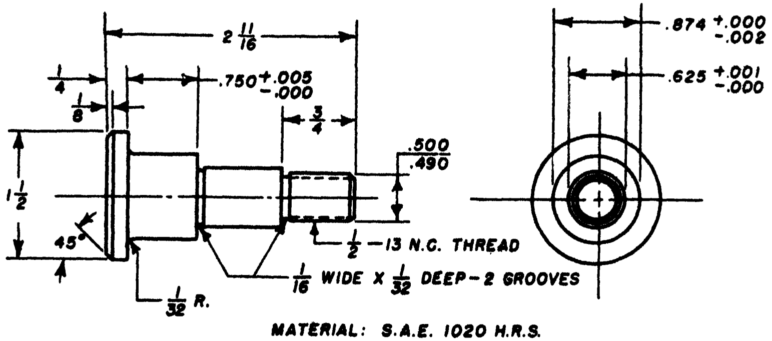


Fig. 74. A stud.

Allow 5 per cent for spoilage and bar ends. Total length of 1½-in. diameter bar stock is:

$$2.875 \times 10 \times 1.05 = 30.188 \text{ in.}$$
$$= 2.516 \text{ ft}$$

For estimating, this figure can be rounded off to 2.6 ft. 1½-in. diameter bar stock weighs 6.008 lb. per foot. At 11 cents per pound the total material cost is:

$$2.6 \times 6.008 \times 0.11 = \$1.72$$

Problem 22. Estimate the cost of the material at 11 cents per pound for 5 studs shown in Fig. 75.

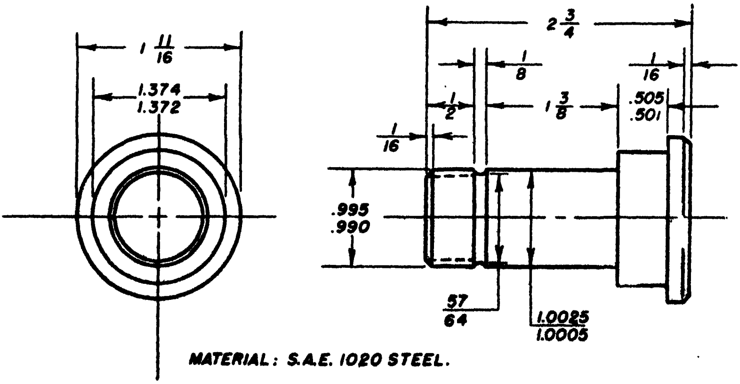


Fig. 75. A timing-gear stud.

Problem 23. Estimate the cost of the material at 11 cents per pound for 25 push rods shown in Fig. 76.

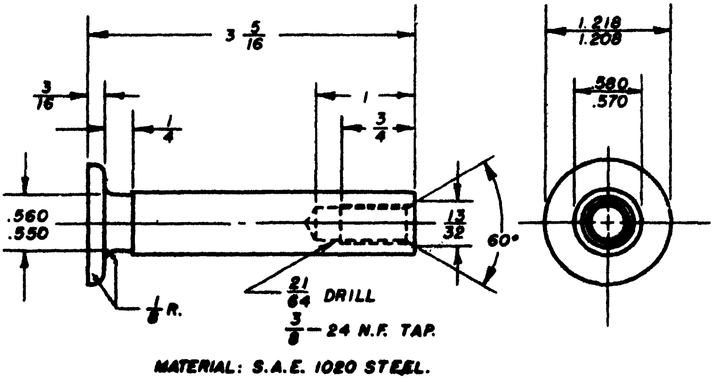


Fig. 76. A valve push rod blank.

For stampings, sheets and strips are used and the size is determined from the dimensions of the blank and from stock sizes available. A narrow margin must be provided around the blank in most cases, although some parts may be cut off without allowance between pieces. An empirical relationship for the scrap allowance on each side of the blank is:

$$S = t + 0.015d \tag{54}$$

where

S = the scrap allowance of each side of the strip in inches. (S is not usually more than $\frac{3}{16}$ in.)
t = thickness of stock in inches.
d = diameter or width of blank in inches.

For the scrap allowance between successive blanks in a strip, an accepted rule is that it should be $\frac{1}{32}$ in. for stock less than $\frac{1}{32}$ in. thick, an amount equal to the stock thickness for dimensions from $\frac{1}{32}$ to $\frac{3}{16}$ in., and a maximum of $\frac{3}{16}$ in. for greater thicknesses. In addition, 5 per cent is usually added to the calculated requirements for waste and spoilage.

Example 12: Find the unit material cost at 9 cents per pound for 3 in. diameter by $\frac{1}{8}$ in. thick disks stamped from cold rolled strip steel. The stock is obtainable in strips $24\frac{3}{4}$ in. wide, weighing 5 lb/ft^2, and will be slit into suitable widths.

Since the space between each blank in the strip must be $\frac{1}{8}$ in., the center distance of two adjacent blanks must be $3\frac{1}{8}$ in.

The scrap allowance on each side of the strip, from Eq. 54 is:

$$S = 0.125 + 0.015 \times 3 = 0.170 \text{ in.}$$

If a single series of blanks are to be stamped from a strip, as illustrated by Fig. 77A, the width of the strip must be:

$$3 + 2 \times 0.170 = 3.340 \text{ in.}$$

Seven strips of this width can be slit from the stock 24¾ in. wide, but that would waste a strip 1⅜ in. wide. If two rows of blanks are nested in each strip, as shown in Fig. 77B, four such strips can be slit from the stock 24¾ in. wide. This arrangement will provide eight rows of blanks with a minimum scrap loss. Each blank will consume an area of strip

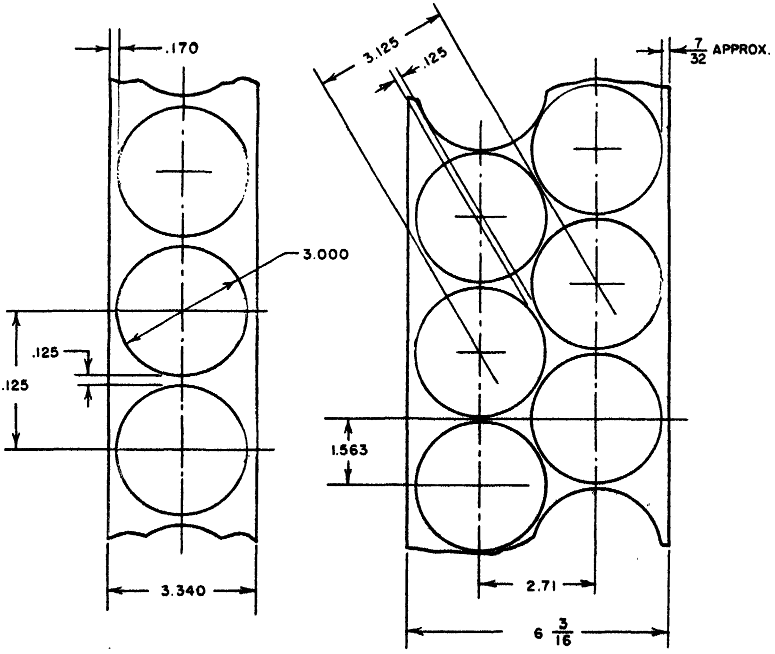
$$1.563 \times 6.188 = 9.67 \text{ in.}^2 \text{ per piece.}$$

Add 5 per cent scrap and end loss:

$$9.67 \times 1.05 = 10.16 \text{ in.}^2 \text{ per piece.}$$

The equivalent weight is:

$$\frac{10.16}{144} \times 5 = 0.353 \text{ lb per piece.}$$



A

SINGLE SERIES OF BLANKS IN A STRIP.

B

TWO ROWS OF BLANKS NESTED IN A STRIP TO SAVE STOCK.

Fig. 77. Stock for round blank.

The cost is

$$0.353 \times 9 = 3.177 \text{ cents per piece}$$
$$= \$3.18 \text{ per 100 pieces.}$$

Problem 24. The strap of Fig. 78 is to be pierced and cut from strip steel 1 in. wide. At a rate of 9 cents per pound, what is the material cost per 1000 pieces?

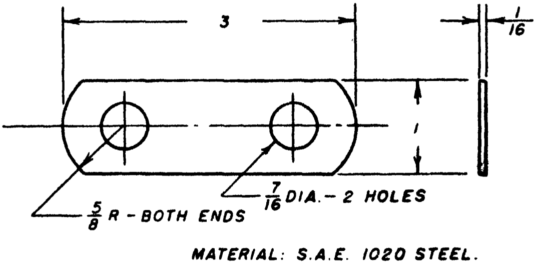


Fig. 78. A strap to be cut from strip.

Problem 25. The piece of Fig. 79 is to be blanked from cold-rolled sheet steel. The stock comes 24¾ in. wide which is to be split into suitable strips. It weighs 1.306 lb/ft^2.

What is an economical width for the strips? What area is consumed for each blank? What is the cost per 1000 pieces?

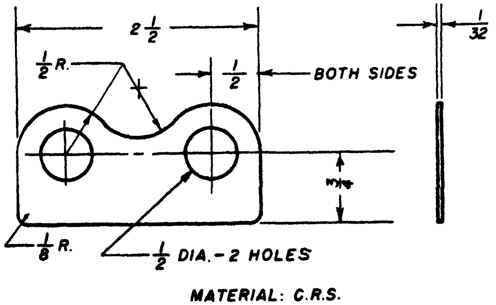


Fig. 79. A flat piece.

For drawn shells, the blank developed from the finished form is sufficiently accurate as a start for estimating material costs, although actually the true blank has a slightly different form because of the working to which it is subjected when drawn.

For cast materials, the weight of the object is estimated by computing or approximating the volume in cubic inches and multiplying it by the specific weight, in pounds per unit of volume. To the finished dimensions should be added the amount of the machining stock. In founding, there are losses from melting, pouring, and cleaning. These may be taken at 10 per cent, to be added to the "as cast" weight. In addition, an allowance is made by some estimators for excess material consumption due to mold imperfections. This is a rather indeterminate factor, depending upon circumstances in the particular foundry, and for many cases can be considered taken care of in the 10 per cent loss factor.

Problem 26. Estimate the weight of the casting of Fig. 5. Assume ⅛ in. of stock on the casting for finished surfaces. At 20 cents per pound, what is the material cost per 100 pieces?

For tools like jigs, fixtures, and dies, standard details like universal jig bodies, die sets, bushings, knobs, and commercial clamping devices may be considered as part of the material to be purchased. The cost of such standard details may be included in material cost. Prices of those items are available in catalogues or from manufacturers' quotations.

Summary of procedure for estimating material cost

The foregoing examples have served to illustrate applications of the universally applicable procedure of material estimating:

1. Determine the necessary additions to dimensions of finished article to account for processing loss from rough to finished states.
2. Calculate unit or lot size or weight in rough condition.
3. Ascertain proportionate extent of unavoidable loss not related to the processing of the individual pieces and increase the rough unit size by that proportion.
4. Multiply the quantity of material by the base price.

ESTIMATING LABOR COST

There are several ways of estimating labor cost, depending upon the degree of accuracy desired. The basic method involves a detailed breakdown of each operation into its elements, a determination of the value of each element, and a summation of all the values. Other methods approximate this synthesis by short cuts. The basic method is able to give the most accurate results and will be presented first to show all that goes into making up labor cost.

Four phases of production

The time needed for practically any production task can be divided into the following four parts:

1. Setup time.
2. Man time (handling).
3. Machine time (cutting, forming, etc.).
4. Maintenance and down time.

Machine time differs from the others because it alone can be calculated.

The elements of an operation

An element of an operation has about the same significance in estimating as it does in time study work, except there is a decided tendency in estimating to combine elements into larger groups to make them easier to handle. The estimator might be termed the inverse of a time study man, because he assigns the elemental values to a job to ascertain what can be expected in the way of performance, whereas the time study analyst measures these elements from actual performance and determines the usable standard values for them. Typical elements are illustrated by the following for a simple drilling operation.

1. Get part.
2. Load drill jig.
3. Clamp part in jig.
4. Position jig.
5. Lower drill to work.
6. Drill hole.
7. Raise drill.
8. Reposition jig.
9. Unclamp.
10. Unload drill jig.
11. Dispose of part.

Operation elements may be large or small, as convenience and application dictate. What is considered an element in one study may in another be part of a larger element. For instance, in the foregoing breakdown "get part," "load drill jig," and "clamp part in jig" were considered separate elements, whereas in another analysis they might very well be grouped together as one element called "load part." Although its content may vary within limits, an element still must conform to logical conditions. It must be a distinguishable entity, be large enough to be readily discernible, and represent a logical unit in manufacturing.

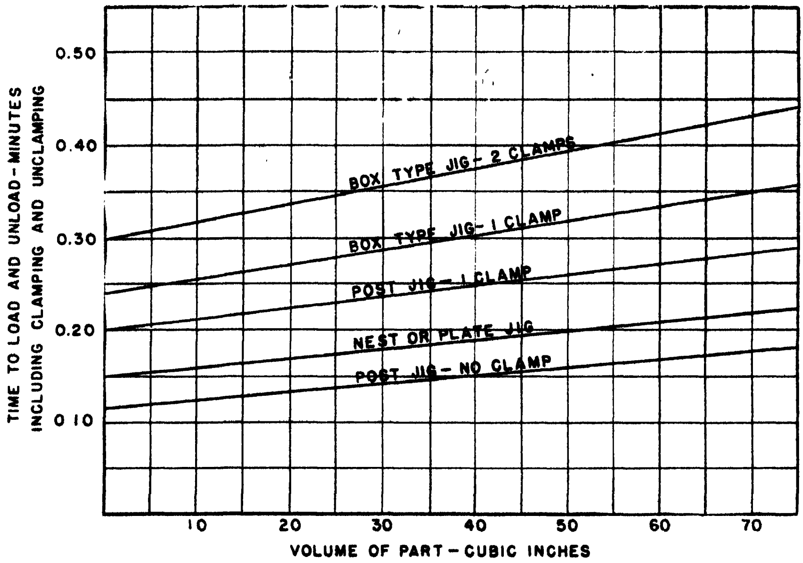


Fig. 80. Loading and unloading time for various kinds of drill jigs.

Characteristic of most machines used in manufacturing is that they do the work for which they are intended by the repetition in various combinations, of a limited number of elements. The value of any one element may not be the same under different conditions, but it is essentially constant for a definite set of conditions wherever it appears. As an example, Fig. 80 shows the time value for loading a part into a jig under specified conditions relating to the bulk of the part and the type of jig. Charts like this and comparable tables are warranted and useful because of the definite relation between the time value of an element and its variable conditions.

An estimator should have an appreciation and understanding of the means of determining elemental values; in other words, an acquaintanceship with the subject of time study. Of equal importance, he must have an intimate knowledge of the details of the processes he is estimating. He must be able to visualize all the steps taken to fabricate an object, conceive of the details of the tools and machines best suited to the operations, and anticipate every move of the operator. With such a background, the estimator is in a position to apply the principles of estimating surely and efficiently.

Setup time

For estimating purposes a production job is divided into operations, and each operation subdivided, so that it may receive appropriate treatment in its various aspects. Setup time is expended by the operator to assemble tools and material, place the tools on the machine, make necessary adjustments and trial runs, and in tearing down. In other words, it includes all the time required to make preparation for the production of good parts in the standard time. Presumably it is charged only once to a lot of parts irrespective of quantity; that is, the machine is set up at the beginning of each run and torn down at the end. If only one part is made, its cost must include the entire setup. If an order of parts is being contemplated and it is likely to be manufactured in several lots, then setup should be charged against the order for as many runs as are expected. From these considerations, it is apparent that setup time for an operation should be treated as a separate entity. A prorated setup time based upon one lot size is not applicable to another lot of different size.

Man time

Man time represents that part of each cycle of an operation during which the machine is not acting on the part. It is often called handling time because it virtually represents that period during which the operator is loading, clamping, cleaning, or disposing of the part. It may also include time for taking measurements and even for rest. However, if the operator performs some duty, such as burring, while the machine is active, that is not an element of man time. The value of man time is that accumulated during one cycle of the operation. For example, in the hypothetical drilling operation, all the elements except #6 (drill hole) added together comprise the man time.

Generally each type of machine has a group of elements peculiar to its operation. Thus, in a plant such as a machine shop, tool shop, or foundry considerable data must be compiled and arranged to cover all the machines and equipment employed. All plants of any size have very complete files of performance data which are carefully restricted and accessible only to persons who must use the information. For machine shop processes excellent and complete tabulations of elements for setup and operation of machine tools have been compiled by W. A. Nordhoff.[3] Table 3 showing the elements for the engine lathe is taken from that reference.

TABLE 3

ENGINE LATHE ELEMENTS

Setup Time	*Minutes*
1. Make up time slip and check in on new job	1.000
2. Study drawing	1.000
a. Add time to compute omitted dimension	1.500
b. Add time for computing a taper	3.000
c. Add time for computing an angle	6.000
NOTE: Blueprints often omit dimensions that can be calculated from other given dimensions. Tapers are seldom given in degrees or in taper per foot. As lathes are usually calibrated in such a manner, the operator must reduce the blueprint dimension to such terms before setting his machine for a taper operation. Sometimes it is necessary for the operator to compute an angle. Time must be allowed for these calculations.	
3. Trip to tool crib to get necessary tools, gages, etc., and to return tools used on previous jobs	5.000
NOTE: Omit this allowance if it is the function of a tool chaser or a production-control clerk to see that the necessary tools, prints, and parts are delivered to the machine.	
4. Constant allowance for each tool handled	0.400
5. Constant allowance for each measuring instrument—calipers, micrometers, depth "mikes," etc.,—necessary for the operator to get from his tool box and set for use on the job	0.750
6. Install three- or four-jaw chuck on lathe spindle	
a. By hand	2.000
b. By jib crane or hoist	5.000
c. By crane	7.000

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[3] W. A. Nordhoff, *Machine Shop Estimating*, First edition, pp. 197–209. New York: McGraw-Hill Book Co., Inc., 1947. Reprinted with the permission of the publisher.

TABLE 3 (Continued)

Setup Time	*Minutes*
7. Install faceplate to lathe spindle	
a By hand	2.000
b. By jib crane or hoist	5.000
c. By power crane (includes crane wait)	7.000
8. Make proper collet selection and install in spindle	0.750
9. Install plain center in spindle	0.500
a. Install center where drawbar is used	1.500
10. Install plain, half, or revolving center in tailstock	0.500
11. Install self-aligning lathe fixture with taper shank and hold-in spindle with a drawbar	1.500
12. Install self-aligning fixture to faceplate by means of dowel-pin locations. Secure fixture by means of T bolts and 4 strap clamps	2.500
13. Install and align fixture on faceplate. Necessary to indicate to align with center of rotation of spindle	10.000
14. Install and align fixture in 3- or 4-jaw chuck. Necessary to indicate and align with center of spindle rotation	10.000
15. Install tool post on cross slide or on compound	0.400
16. Install toolholder in tool post	0.300
17. Install turn-tool bit in toolholder and adjust for proper cutting angle	0.500
18. Install single-end thread tool in toolholder and adjust for proper cutting angle	1.500
19. Install boring bar and tool in compound tool post and adjust for proper cutting angle	1.000
20. Set up taper attachment (includes time for complete adjustment of attachment and tool, trial cuts, and the necessary micrometer work)	10.000
21. Set up and adjust compound and tool to cut taper	1.500
22. Set up tailstock off center for cutting taper, adjust tool, trial cuts, and necessary work to meet dimensions	15.000
23. Install drill chuck, reamers, etc., in taper sleeve adapters for operation from tailstock	0.500
24. Install steady rest and adjust	1.500
25. Install centers in head and tailstock, position and adjust tailstock for work that is to be turned and held between centers	1.200
26. Deliver first piece to inspector (do not wait for inspection, and omit where there is floor inspection)	0.700
Teardown Elements	
1. Sign out on completed job	1.000
2. Separate taper-shank tools from adapter sleeves (each)	0.250
3. Remove cutting tools from holders and store in proper place (each)	0.250
4. Remove toolholders and store in proper place (each)	0.250
5. Remove tool posts and store in proper place (each)	0.350
6. Clean measuring instruments and return to tool chest	0.250
7. Remove chuck or faceplate from spindle	
a. By hand	1.000
b. By jib crane or hoist	4.000
c. By overhead crane (wait for crane included)	6.000
8. Remove collet chuck from spindle	0.300

TABLE 3 (Continued)

Setup Time	*Minutes*
9. Remove live center from spindle	
a. Without drawbar	0.300
b. With drawbar	1.000
10. Remove center from tailstock	0.300
11. Remove taper-shank fixture (with drawbar) from spindle, and aside to floor	1.200
12. Remove fixture from faceplate (release and aside with 4 clamps) and aside to floor	1.500
13. Release fixture from chuck jaws, and aside to floor	1.000
14. Blow fixture clean for storage	0.400
15. Disengage taper attachment	1.500
16. Return compound from taper to normal position	0.400
17. Return tailstock from taper to center position (includes time to indicate to be sure centers are in line)	5.000

Operation Elements

A. Material installation

NOTE: The time shown also *includes the time to release the part from its respective holding device and its disposition to floor or tote pan.* The description of the element will show only its installation.

1. Bar- and tube-stock installation (where fed through the spindle)	
a. Release universal chuck, move material out by hand, scale for proper amount of stock, and secure material in chuck for work	0.450
2. Bar- and tube-stock installation (where stock is cut to the approximate length)	
a. Pick up piece, install in universal chuck	0.300
b. Pick up piece, install in universal chuck, align by hand, and secure for work	0.600
c. Pick up piece, install in universal chuck, align by use of a micrometer dial indicator, and secure for work	1.200
d. Pick up piece, install in collet chuck, and secure for work	0.300
3. Bar and tube stock (where necessary to support with a steady rest):	
a. Pick up piece, position in universal chuck and steady rest, secure for work	0.400
b. Pick up piece, position in universal chuck and steady rest, align by use of a dial micrometer indicator, and secure for work	0.900
4. Bar and tube stock (where supported between centers)	
a. Pick up piece, install lathe dog on part, position between centers, secure for work	
(1) Small parts	0.300
(2) Medium parts	0.750
(3) Large parts	1.000
5. Semifinished bar, tube, and casting parts	
a. Pick up part, insert in split bushing, insert in universal chuck, and secure for work	0.350
b. Pick up part, insert in split bushing, insert in collet chuck, and secure for work	0.150
c. Pick up part, install on mandrel, and secure for work	0.800

TABLE 3 (Continued)

Setup Time	*Minutes*
6. Installation of castings, forgings, etc., in lathe fixture	
a Pick up part, install in lathe fixture	
(1) Small or regular parts	0.700
(2) Small irregular or medium regular parts	1.100
(3) Large or medium irregular parts	2.000
(4) Large irregular parts	2.500
NOTE: Where necessary to align part with a dial indicator because of a concentricity note, allow indicating time and add to the above	1.000
7. Installation of a casting in an independent chuck (no fixture)	
a. Pick up part, position between jaws of an independent chuck, align, and secure for work	
(1) Small and regular parts	1.000
(2) Small irregular and medium regular parts	1.400
(3) Large or medium irregular parts	2.300
(4) Large irregular parts	2.800
NOTE: Where necessity to align part with a dial indicator, because of a concentricity note, allow indicating time and add to the above	1.000
B. Turning operations	
1. Straight turning from cross slide	
a. Move cross slide into position, set tool to proper depth of cut, advance tool to work, engage feed	0.200
b. Rough-turn.	
c. Back cross slide and tool from work, set tool to proper depth by micrometer dial on hand-feed wheel, advance tool to work, engage feed	0.300
d. Trial cut.	
NOTE: The length of this cut should be long enough to accommodate a check on the diameter with either a pair of calipers or "mikes." Maximum trial cut should be ¼ in. in length.	
e. Second-rough- or semifinish-turn.	
f. "Mike" diameter	0.200
g. Back cross-slide tool from work, set tool proper depth by micrometer dial on hand-feed wheel, advance tool to work, engage feed	0.300
h. Trial cut.	
NOTE: See d. above.	
i. Back up tool "mike," make final adjustments for cut, advance tool, engage feed	0.400
j. Finish-turn.	
k. "Mike" for final check of turn operation	0.200

NOTE: The number of cuts will depend on the amount of stock to be removed. Where the part is well supported and rigidly held (that is, chucked close, held between centers, supported by a steady rest, etc.) roughing cuts of ⅛ to ½ in. should be taken. Where stock cannot be well supported, roughing cuts of ⅛ in. will prevail.

Rough-turning operations are primarily for the removal of excess stock. The cutting speed should be the maximum for that material for depths of cuts of ⅛ in. or less. Feeds of 0.015 to 0.032 should be employed. Where the depth of the rough cut is ¼ to ½ in., it is customary to slow the speed down and reduce the feed to 0.015.

TABLE 3 (Continued)

Setup Time	*Minutes*
Stock left for finish cuts should be between 0.005 and 0.030. Maximum cutting speeds and feeds from 0.005 to 0.015 are utilized. Feeds used in finish cuts are limited only by the skill of the operator to put the required finish on the part at the greatest possible feed.	
If the turned diameter is to be ground, grinding stock of approximately 0.010 should be left. The lathe finish is not so important. In fact, tool marks on the diameter to be ground are an asset to the grinding operation.	
2. Forming	
a. Change tool in cross slide tool post, set to proper angle for cut	0.400
b. Move cross slide into proper position, advance tool to work	0.200
c. Form-turn.	
d. Back from work, position tool into clear	0.100
3. Clean out corners	
a. Advance tool to proper depth, clean out corner by hand feed, and back tool into clear	1.000
NOTE: The operation is usually necessary where two finish surfaces form an inside corner at 90°.	
4. Form fillets	
a. Change tool (with proper radius) in tool post, and set in proper position for work	0.400
b. Advance tool to work	0.100
c. Cut one fillet	0.200
NOTE: Most fillets can be cut with a few turns, and the feed is by hand.	
d. Back tool away, position to next fillet to be cut	0.150
e. Cut fillet	0.200
f. Repeat 4 and 5 for the balance of fillets to be cut.	
g. Back tool into clear	0.100
5. Form radius	
a. Change tool in tool post, and set in proper position for work	0.400
b. Advance tool to work	0.100
c. Cut radius	0.200
NOTE: Repeat 4 and 5 for the balance of radii to be cut.	
d. Back up tool, position to next radius to be cut	0.150
e. Cut radius	0.200
NOTE: Repeat 4 and 5 for the balance of radii to be cut.	
f. Back tool into clear	0.100
6. Chamber	
a. Release tool post, swing into proper angle for cut, secure tool post, advance tool to work	0.250
or	
Advance tool to work	0.100
b. Chamfer.	
c. Back tool into clear	0.100
7. Turn relief	
a. Advance tool to work, scale for proper position of cut, or set by micrometer dial	0.150
b. Hand-feed cut to proper depth of relief, engage feed.	

TABLE 3 (Continued)

Setup Time	*Minutes*
c. Trial cut (maximum length of trial cut should be ¼ in.).	
d. "Mike" cut, set tool proper depth by hand-feed micrometer dial, and engage feed	0.300
e. Turn relief.	
NOTE: Usually one cut is sufficient to turn a relief. If more than one cut is required, repeat elements a, b, c, d, and e.	
f. Time to check length of cut with rule	0.200
g. Back tool into clear	0.100
8. Cut groove	
a. Change tool in tool post, and set tool for proper position for cutting	0.400
b. Advance cross slide tool and scale for proper position of the cut	0.200
c. Turn groove.	
NOTE: This is usually a hand-feed operation, with proper depth noted on feed-wheel micrometer dial, and the tool is the exact width of the groove. If there is more than one groove of the same width, repeat the following:	
d. Back tool from work, move to proper position to turn next groove, scale for proper dimension	0.150
e. Turn groove.	
f. Back tool into clear	0.100
9. Turn thread relief	
a. Change tool in tool post and adjust for work	0.400
b. Advance tool to work	0.100
c. Cut thread relief (hand-feed operation)	
d. Back tool from work and into clear	0.100
10. Short tapers	
a. Release compound rest, swing to proper angle, and secure	0.500
b. Advance tool to work	0.100
c. Turn taper.	
NOTE: One cut; hand feed.	
d. Back tool from work	0.100
e. Release compound rest, swing back into normal position, secure	0.400
NOTE: It is not always necessary to change the position of the compound rest to cut these short tapers. Straight turning and facing can be done with the compound rest set at an angle. If the compound rest is set up at the desired angle and the nature of the work permits its remaining in that position, use the following to cut short tapers:	
a. Advance tool to work	0.100
b. Cut taper.	
c. Back tool from work	0.100
11. Long tapers	
a. Pick up piece, and install in suitable manner in lathe for work	See A
NOTE: Because of the setup involved, long tapers should be performed as a separate, independent operation.	
b. Bring cross slide into position, advance tool to work, set tool proper depth, engage feed	0.200
c. Cut taper (first cut).	
d. Back tool from work, position tool, set proper depth, engage feed	0.200

TABLE 3 (Continued)

Setup Time	*Minutes*
e. Cut taper (second cut).	
f. Repeat d and e for the balance of the cuts.	
NOTE: Maximum length of cut reached on finish-turn taper. The number and lengths of cuts will vary with the depth, the length, and the angle of the taper.	
g. Release piece from machine, and aside to floor.	
h. Allow time to check work	1.000
12. Cut threads—internal and external—single-pointed thread tool.	
a. Release compound rest, swing into proper position, and secure	0.400
b. Change tool in toolholder, set in proper position, and secure	0.400
c. Position tool, set tool proper micrometer depth, start machine, engage feed at the proper lead	0.200
d. Cut thread (first cut)	
e. Position tool, set tool proper micrometer depth, engage feed	0.150
f. Cut thread (second cut).	
g. Position tool, set tool proper micrometer depth, engage feed	0.150
h. Cut thread (third cut).	
i. Position tool, set tool proper micrometer depth, engage feed	0.150
j. Cut thread (fourth cut).	
k. Position tool, set tool proper micrometer depth, engage feed	0.150
l. Cut thread (fifth cut).	
m. Position cross slide into clear	0.100
n. Blow threaded area clean with blowgun	0.080
o. Check with gage	0.300
p. Position tool, set tool proper micrometer depth, engage feed	0.150
q. Cut thread (sixth cut).	
r. Position cross slide into clear	0.100
s. Blow threaded area clean with blowgun	0.080
t. Check with "go" gage	0.400
u. Check with "no go" gage	0.200
v. Clean up threads (remove burrs) with emery cloth	0.400
NOTE: For cutting threads on aluminum, brass, bronze, or magnesium alloys, eliminate elements, g, h, i, j, k, and l.	
C. Boring operations	
1. Straight boring with boring bar installed between centers and fixtures mounted on cross slide	
a. Pick up piece, and install in fixture on cross slide carriage	See A
b. Pick up rough-boring bar, position through part to be bored, attach drive dog to bar, position bar between centers, and secure	1.000
c. Move cross slide and work into position to bore	0.100
d. Rough-bore.	
e. Move work into clear	0.100
f. Release rough-boring bar from between centers, remove driver, and aside with bar	0.500
g. Pick up second-rough-boring bar, position in bore, attach driver dog to bar, position bar between centers, and secure for work	1.000
h. Move cross slide and work into position to bore	0.100
i. Second-rough-bore.	
j. Move work into clear	0.100

TABLE 3 (Continued)

Setup Time	*Minutes*
k. Release boring bar from between centers, remove driver, and aside with bar	0.500
l. Pick up finish-boring bar, insert in bore, install driver dog, position between centers, and secure for work	1.000
m. Move work into position for work	0.100
n. Finish-bore.	
o. Move work into clear	0.100
p. Release finish-boring bar from between centers, remove driver, and aside with bar	0.500
q. Release part from fixture.	
r. Allow checking time	0.500
2. Straight boring (from cross-slide tool)	
a. Change compound rest setup from turning to boring	1.100
NOTE: Where boring bar with single- or double-end tool is used, the bores are longer than 1 in., have close tolerances, are larger than efficient drill and reamer sizes, etc.	
b. Change tool in tool post, and alter angle of tool	0.500
NOTE: For short bores and counterbores	
c. Move cross slide into position, set tool proper depth for cut, advance tool to work, engage feed	0.200
d. Rough-bore.	
e. Back tool from work, set tool micrometer depth for next cut, advance tool to work, engage feed	0.300
f. Trial cut.	
NOTE: Length of this cut should be long enough to accommodate a pair of calipers or inside "mikes." Maximum length of trial cut to be ¼ in.	
g. Second-rough bore.	
h. Back tool from work, "mike" bore	0.300
i. Set tool proper micrometer depth, advance tool to work, engage feed	0.300
j. Trial cut.	
k. Back tool from work, "mike" bore, make final tool adjustments for cut, advance tool to work, engage feed	0.300
l. Finish-bore.	
NOTE: The number of boring cuts will depend on the amount of stock to be removed. Where part is well supported, roughing cuts of ⅛ to ¼ in. should be taken. Where stock cannot be well supported and has a tendency to "spring" or where the boring tool extends a considerable distance from its main support, depths of less than ⅛ in. will be necessary. If the bore is to have a grind finish or is to be honed, grinding stock of approximately 0.010 in. should be left and the lathe finish is not so important.	
3. Counterbores (undercut or internal relief)	
a. Position tool inside of bore to the proper position, hand-feed tool to proper depth (both positions determined by machine micrometer dials), engage feed	0.300
b. Add time to the above to hand-feed into proper depth of cut.	

TABLE 3 (Continued)

Setup Time	*Minutes*
c. Counterbore.	
d. Repeat a, b, and c, if more than one is necessary to complete the counterbore.	
Note: Internal counterbores are usually for clearance only and can be completed on one cut.	
e. Back tool from work, and position into clear	0.100
4. Counterbores (external)	
a. See straight boring (C1 and C2 above). The elements of this operation will follow the same pattern and the time values will be the same.	
5. Cut internal-thread relief	
a. Change tool in boring bar, adjust for work	0.400
b. Position tool to work and set by micrometer dial	0.200
c. Cut relief	0.200
Note: This operation usually requires only a few turns to complete, and the feed is by hand.	
d. Back tool from work and position into clear	0.100
6. Taper bore (short taper).	
a. Release compound rest, swing into proper position, and secure	0.500
b. Change tool in toolholder	0.300
c. Advance tool to proper position for work	0.200
d. Cut taper (one cut).	
e. Back tool from work	0.100
f. Release compound rest, swing back into normal position, secure	0.400
7. Taper bore (long taper)	
a. Pick up piece, and install in lathe in a suitable manner for work	See A
Note: Because of the time involved in setting up the taper attachment or the tailstock to cut a taper, long tapers should be bored as a separate, independent operation.	
b. Bring cross slide into position, advance tool to work, set tool proper depth, engage feed	0.300
c. Cut taper (first cut).	
d. Position tool, set proper depth, engage feed	0.300
e. Cut taper (second cut).	
f. Repeat d and e for balance of cuts.	
Note: Maximum length of cut will be reached on "finish-bore taper." The number of cuts will vary with the depth, the length, and the angle of the taper.	
g. Position tool into clear	0.100
h. Allow time to check work	1.000
8. Internal forming	
a. Change tools in tool post, and check	0.400
b. Advance tool to work	0.100
c. Form.	
d. Back tool from work and into clear	0.100
e. Time to check work	0.500
9. Chamfer	
a. Position tool into proper position for work	0.100
b. Chamfer.	

TABLE 3 (Continued)

Setup Time	*Minutes*
c. Back tool into clear	0.100
10. Cut threads (internal).	
a. Cut threads—internal and external.	
D. Facing operations (from cross slide)	
1. Straight facing (clean-up only)	
a. Position cross slide, set tool proper depth for cut, advance tool to work, engage feed	0.150
b. Face (one cut).	
c. Position tool into clear	0.100
2. Face (fractional dimension)	
a. Position cross slide, set tool proper depth for cut, advance tool to work, engage the feed	0.150
b. Rough-face.	
c. Back tool from work, scale or caliper	0.200
d. Set tool proper depth, advance tool to work, engage feed	0.150
e. Finish-face.	
f. Check dimension	0.100
g. Position tool and cross slide into clear	0.100
3. Face (decimal dimension)	
a. Position cross slide, set tool proper depth for cut, advance tool to work, engage feed	0.150
b. Rough-face.	
c. Back tool from work, scale or caliper	0.200
d. Set tool proper micrometer depth, advance tool to work, engage feed	0.150
e. Second-rough-face.	
f. Back tool from work, "mike"	0.300
g. Set tool proper micrometer depth, advance tool to work, engage feed	0.150
h. Trial-cut, "mike," reset tool proper depth, advance to work, engage feed	0.400
i. Add time to make trial cut. Maximum length cut should be ½ in.	
j. Finish-face.	
NOTE: The number of cuts will depend on the amount of stock to be removed. Minimum depth of cuts should be ⅛ in. until finish cut is reached.	
4. Cut serrations (form tool)—cut groove (form tool)	
a. Change tools in tool post and check	0.400
b. Advance tool to proper position to work	0.100
c. Cut serrations (or groove).	
d. Back from work, and position cross slide into clear	0.100
e. Time to check work	0.500
E. Tailstock operations	
1. Center-drill, drill, ream, etc.	
a. Position tool into clear, release tailstock from ways, position tailstock into clear	0.150
b. Change tools in drill chuck installed in tailstock, and secure	0.200
c. Change tools having (or installed in) taper shanks in tailstock	0.150
d. Position tailstock to work. lock to ways, advance tool to work	0.200

TABLE 3 (Continued)

Setup Time	*Minutes*
e. Start reamer by hand	0.300
f. Start tap or button die by hand	0.500
g. Machine dimension.	
1) Center-drill.	
2) Drill.	
3) Ream.	
a) Brush oil on reamer	0.100
4) Counterdrill (counterbore).	
5) Countersink.	
6) Tap or thread with button die.	
a) Brush oil on tap or die.	
h. Allow time to check drilled hole	0.200
i. Allow time to check tapped hole	0.300
F. Miscellaneous operations	
1. Break edges with file (per machined edge)	0.050
2. Chamfer 45° by 1/32 in. (done with file)	0.100
3. Cutoff operation (bar stock or tubing)	
a. Change tools in tool post, and check	0.400
b. Scale for cut, position tool to work	0.150

Allowances

Man time allowances. In addition to actual working time, provision must be made for other unavoidable activities constituting a real part of an operation, but not reflected in its elements. These include time out for personal needs, fatigue, cutter sharpening, checking, and miscellaneous chores. Allowances added to the sum of the observed elements of each operation are the common means of providing for the excess legitimate time. The amounts of the allowances vary from plant to plant depending upon specific conditions in each establishment. However, there are logical principles applicable universally to the determination of allowances.[4]

Human beings anywhere have been found to require a minimum of 5 per cent of their working time for *personal needs* if they are to work efficiently. In addition, cognizance must be taken of physical and mental *fatigue* and additional *allowances* provided to overcome the resulting impairment of the workman's faculties. Whether approval is given or not, a man's physical nature compels him to slow down when the limit of endurance is approached. There is a direct relationship between the amount of time that must be allowed for recuperation and the intensity of effort required. On some machines there are periods during long cuts when rest can be taken without interference with work progress. Light tasks demand a smaller allowance for fatigue than do heavier ones.

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[4] Nordhoff, *op. cit.*, pp. 65–75.

In general, 5 per cent is sufficient for fatigue allowance where automatic machinery is being operated or on jobs where cuts are quite long, 15 minutes or more. A 10 per cent allowance may be needed for automatic machinery working to close tolerances and on other power-driven machines where the cutting time exceeds the handling time by only a small margin: 15 to 20 per cent is applicable to operations where the cutting time is small and 25 per cent or more for heavy continuous work or close and exacting applications.

Allowances for tool sharpening are related to tool life. If

T_1 = the amount of time needed to change a tool, in minutes,
t = the time to be added to a cycle of an operation for its prorated share of the tool change time, in minutes,
T_2 = time during which the tool is cutting in one cycle of the operation, in minutes,
T = length of life of tool, in minutes,

then

$$t = \frac{T_1 \times T_2}{T} \tag{55}$$

Two considerations determine *checking allowance;* the time required for each measurement and the frequency of checks. The time required to make a check with a gage or take a measurement with an instrument is related to the surface geometry and the kind of instrument used. Generally, outside surfaces, particularly diameters, are the easiest to check. Average observations consume from 0.10 to 0.20 minutes. Inside surfaces require more time, 0.20 to 0.30 minutes. The frequency of observations depends upon both the nature of the operation and the tolerance of the dimension. If the part can be checked out of the machine and the operator has time to do so while a cut is being taken, no allowance may be necessary. Automatic machinery will obviously be more dependable than engine lathes, which must be readjusted for each cut, and frequency of checking will differ accordingly between the two. Very close dimensions, under 0.0005 in., will probably have to be checked for each piece; whereas fractional dimensions may need to be checked only once in several hundred pieces. Many experience tables of checking time and frequency have been compiled and a few have been published. If

n = number of parts between checks plus one,
$f = 1/n$ = frequency of checking,
T_c = checking time for a specific dimension,
t_c = the time to be added to a cycle of an operation for its prorated share of time to check the dimension,

then
$$t_c = \frac{T_c}{n} = T_c f \tag{56}$$

The total checking allowance for an operation then is the sum of the values of t_c for all dimensions.

Machine time

All machine tool calculations for machine time must lead to the fundamental relationship that:

$$T_m = \frac{L}{F} \tag{57}$$

where
T_m = time for cut in minutes,
L = length of cut in inches,
F = feed of tool in inches per minute.

The sum of all the values of T_m for a cycle is the machine time of an operation.

The length of cut (L) is the distance that the tool (or workpiece) is fed in order to cut away material, plus two increments, overtravel and approach. It is not always practical to bring a tool precisely to the edge of the surface that it is to cut, nor always to stop it exactly at the other end, particularly if it is being operated in a preset cycle. The small additions to the tool travel occasioned by these situations constitute the *overtravel*. The length thereby added to the cut usually varies from $\frac{1}{32}$ to $\frac{1}{4}$ in.

Approach is excess travel attributable to the forms of certain tools, most commonly drills and milling cutters. In the case of a drill, it is the length of the point, which for the common 118° point angle is very close to the diameter of the drill, multiplied by 0.289.

For milling cutters, approach is different for roughing cuts from what it is for finishing. It is also different for face milling from the way it is applied to slab milling. For rough face milling the cutter needs only to contact the entire surface. Therefore, as shown in Fig. 81A, the face mill feeds from its starting position in contact with the work a distance A (the approach) until it is cutting the full width w of the surface and then continues cutting for a distance equal to the length of the surface. In Fig. 81A,

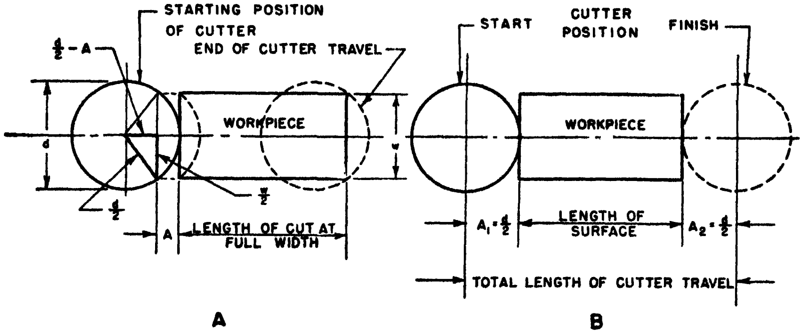


Fig. 81. (A) Approach of face mill for roughing cut. (B) Total approach of slab or slot milling cutter.

d = diameter of face mill, in inches,
w = width of work piece face, in inches,
A = approach, in inches,

from the triangle having the sides $d/2 - A$, $w/2$, and $d/2$;

$$\left(\frac{d}{2} - A\right)^2 + \left(\frac{w}{2}\right)^2 = \left(\frac{d}{2}\right)^2$$

from which

$$A^2 - Ad + \frac{w^2}{4} = 0$$

and

$$A = \frac{d \pm \sqrt{d^2 - w^2}}{2} \tag{58}$$

$$= \frac{d}{2} - \sqrt{\frac{d^2 - w^2}{4}}$$

As w approaches d, A becomes more nearly $d/2$, which is often a close approximation.

For finish face milling, good workmanship prescribes that the cutter pass entirely over the surface so that its trailing edge can get in its full wiping action. From Fig. 81B, showing this condition, it should be obvious that for finishing, A is equal to d.

The approach of the cutter in slab milling is illustrated in Fig. 82. From the triangle inscribed in the cutter outline,

$$A^2 + \left(\frac{d}{2} - c\right)^2 = \left(\frac{d}{2}\right)^2$$

$$A = \sqrt{cd - c^2} \qquad (59)$$

where c = depth of cut.

Most handbooks have tables of approach for milling based on the foregoing equations.

Speed and feed. The basis for determining feed differs for all types of machine tools. With all, however, the starting point is the speed of the cutter, the linear rate in feet per minute at which the cutter travels through the work material. Cutting speed is affected by a number of variables and its ultimate determination is an economic as well as a physical problem. For that reason many tables advocating widely different cutting speeds will be found in handbooks and texts, as explained in Chap. 3. It should be understood that no general recommendations can be made for speeds and feeds to meet competitive conditions. Actually, an estimator adopts cutting speeds conforming to the practice in his plant.

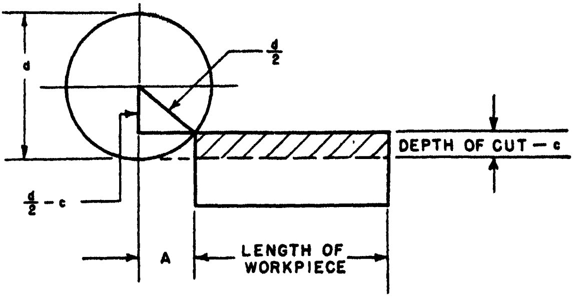


Fig. 82. Approach of slab or slot milling cutter.

For a revolving workpiece or cutter the cutting speed is taken at the periphery. To find the equivalent turning rate in revolutions per minute:

$$N = \frac{C.S.}{\pi d/12} = \frac{12\,C.S.}{\pi d}$$

Or, in simplified form sufficiently accurate for most calculations:

$$N = \frac{4\,C.S.}{d} \tag{60}$$

where

N = rotating speed, in revolutions per minute,
$C.S.$ = peripheral cut speed, in feet per minute,
d = diameter of revolving cutter or workpiece, in inches.

The feed rate (F) in inches per minute is the product of the feed (f) in inches per revolution multiplied by the number of revolutions per minute.

$$F = Nf \tag{61}$$

To arrive at the cutting time T_m by detailed calculations, using Eqs. 57, 60, and 61, is too tedious for practical purposes. Many charts and special slide rules have been devised as short cuts. Figure 83 shows one of them. For the specified diameter, the desired cutting speed is selected in the left-hand section of the chart. In the same line, to the right, under the appropriate feed in inches per revolution, the resulting reciprocal of the feed (F), in minutes per inch, is given. This last figure need only be multiplied by the length of travel L for the cutting time (T_m).

Feed, like speed, is dependent upon a number of variable conditions and is different for each set. For estimating purposes, average values for feeds for turning, facing, and allied operations are available in handbooks or may be tabulated from current practice in any particular plant. In choosing a specific feed from the range offered, the estimator must use judgment. Such factors as the rigidity and power of the machine and strength or frailty of the workpiece help determine whether a high feed or low feed is applicable. A light machine or frail workpiece cannot be expected to withstand heavy feed. If an estimate is to be made of a job performed on a specific make and model of machine tool, the exact speeds and feeds chosen will, of course, be those provided by the machine nearest to the indicated optimum. A tool with a small nose must be given a finer feed for finishing than a broad nose tool.

For the milling process, the feed rate is derived from the thickness of chip taken by each tooth of the cutter. That is the distance the work advances between the time one tooth impinges upon it and the instant the next tooth contacts it. A number of variables

DIAMETER IN INCHES																						FEED PER REVOLUTION IN THOUSANDTHS										
½	⅝	¾	⅞	1	1⅛	1¼	1⅜	1½	1⅝	1¾	1⅞	2	2⅛	2¼	2⅜	2½	2⅝	2¾	2⅞	3	R.P.M.	.002	.004	.007	.010	.015	.020	.025	.031	.046	.060	.090
.13	.16	.20	.23	.26	.29	.33	.36	.39	.43	.46	.49	.52	.56	.59	.62	.65	.69	.72	.75	.79	1	500.	250.	143.	100.	67.	50.	40.	32.	22.	17.	11.
																					6 9	83.30 55.55	41 65 27.78	23.82 15.89	16.66 11.11	11.16 7.44	8.33 5.56	6.66 4.44	5.23 3.56	3.66 2.44	2.83 1.89	1.83 1.22
																					12 15	41 65 33.30	20.83 16 65	11.91 9.52	8.33 6.66	5.58 4.46	4.17 3 33	3.33 2.66	2.67 2.13	1.83 1.47	1.42 1.13	.91 .73
																	17	18	19	20	19 25	26.30 20.00	13.15 10.00	7.52 5.72	5.26 4.00	3.52 2.68	2.63 2 00	2.10 1.60	1.68 1.28	1.16 .88	.89 .68	.58 .44
									17	19	20	16 21	17 23	18 24	19 25	20 27	21 28	22 30	23 31	24 32	31 41	16.10 12.15	8.05 6.08	4.60 3.47	3 22 2.43	2.16 1.63	1.61 1.22	1.29 .97	1.03 .78	.71 .53	.55 .41	.35 .27
				18	20	15 22	19 24	20 27	22 29	24 31	26 33	27 35	29 38	31 40	32 42	34 45	36 47	37 49	39 51	41 53	52 68	9.60 7 35	4.80 3.68	2.75 2.10	1.92 1.47	1.29 .98	.96 .74	.77 .59	.61 .47	.42 .32	.32 .25	.21 .16
	17	18 22	19 25	22 29	25 32	27 36	30 40	33 43	36 47	38 50	41 54	44 58	47 61	49 65	52 68	55 72	58 76	60 79	63 83	66 86	84 110	5 95 4 55	2.98 2.28	1.70 1.30	1.19 .91	.80 .61	.60 .46	.48 .36	.38 .29	.26 .20	.20 .15	.13 .10
18	20 23	25 27	29 32	33 37	37 41	41 46	45 50	49 55	53 60	57 64	61 68	65 73	70 78	74 82	78 87	82 92	86 96	90 101	94 105	98 110	125 140	4.00 3.55	2.00 1.78	1.14 1.02	.80 .71	.54 .48	.40 .36	.32 28	.26 .23	.18 .16	.14 .12	.09 .08
21 24	26 29	31 35	37 41	42 47	47 53	52 59	58 65	63 71	68 77	73 82	78 88	84 94	89 100	94 106	99 112	105 118	110 123	115 130	120 135	126 141	160 180	3.15 2.75	1.58 1.38	.90 .79	.63 .55	.42 .37	.32 .28	.25 .22	.20 .18	.14 .12	.11 .09	.07 .06
26 29	33 37	39 44	46 52	52 59	59 66	65 74	72 81	79 88	85 96	92 103	98 110	105 118	111 125	118 133	124 140	131 147	137 155	144 162	150 169	157 177	200 225	2.50 2.20	1.25 1.10	.72 .63	.50 .44	.34 .29	25 .22	.20 .18	.16 .14	.11 .10	.08 .07	.05 .05
33 38	41 48	49 57	57 67	65 76	74 86	82 96	90 105	98 115	106 124	115 134	123 143	131 153	139 162	147 172	155 182	164 191	172 201	180 210	188 220	196 229	250 292	2.00 1.70	1.00 .85	.57 .49	.40 .34	.27 .23	.20 .17	.16 14	.13 .11	.09 .07	.07 .06	.04 .04
43 49	54 61	65 74	76 86	86 98	97 110	108 123	119 135	130 147	140 160	151 172	162 184	173 196	184 209	194 221	205 233	216 245	227 258	238 270	248 282	259 295	330 375	1.50 1.30	.75 .65	.43 .37	.30 .26	.20 .17	.15 .13	.12 .10	.10 .08	.07 06	.05 .04	.03 .03
56 64	70 80	83 96	97 112	111 127	125 143	139 159	153 175	167 191	181 207	195 223	209 239	223 255	236 271	250 287	264 303	278 319	292 335	306 351	320 367	334 382	425 487	1 15 1.00	.58 .50	.33 .29	.23 .20	.15 .13	.12 .10	.09 .08	.07 .06	.05 .04	.04 .03	.03 .02
72 82	90 102	108 123	126 143	144 164	162 184	180 205	198 225	216 245	234 266	252 286	270 307	268 327	306 348	324 368	342 389	360 409	378 430	396 450	414 470	432 491	550 625	.90 .80	.45 .40	.26 .23	.18 .16	.12 .10	.09 .08	.07 06	.06 05	.04 .04	.03 .03	.02 .02
91 104	112 128	140 160	161 184	182 208	203 232	231 264	252 288	273 312	301 344	322 368	343 392	364 416	392 448	413 472	434 496	455 520	483 552	504	525	553	700 800	.71 .62	.36 .31	.20 .18	.14 .12	.09 .08	.07 .06	.06 .05	.05 .04	.03 .03	02 .02	.01 .01
117 130	144 160	180 200	207 230	234 260	261 290	297 330	324 360	351 390	387 430	414 460	441 490	468 520	504	531	558						900 1000	.55 .50	.28 .25	.16 .14	.11 .10	.07 .07	.05 .05	.04 .04	.03 .03	.02 .02	.02 .02	.01 .01
143 156	176 192	220 240	253 276	286 312	319 348	363 396	396 432	429 468	473 516	506	539										1100 1200	.45 .42	.23 .21	.13 .12	.09 .08	.06 .05	.04 .04	.04 .03	.03 .03	.02 .02	.01 .01	.01 .009
169 182	208 224	260 280	299 322	338 364	377 406	429 462	468 504	507 546	559												1300 1400	.38 .36	.19 .18	.11 .10	.08 .07	.05 .05	.04 .03	.03 .02	.02 .02	.02 .01	.01 .01	.008 .008
195	240	300	345	390	435	495	540														1500	.33	.16	.09	.07	.04	.03	.02	.02	.01	.01	.007
PERIPHERAL SPEED IN FEET PER MINUTE																					TIME IN MINUTES PER INCH											

Fig. 83. Chart for quickly computing time in turning various diameters. (Courtesy The Monarch Machine Tool Co., Sidney, Ohio.)

affect the permissible magnitude of the feed; type of cutter, work and cutter material, depth of cut, finish desired, rigidity of work, machine, and fixture, the power available, and the nature of the application.

For the feed rate (f), in inches per revolution,

$$f = nt \tag{62}$$

where

n = number of teeth in cutter,
t = unit feed or chip thickness, in inches per tooth.

From there Eq. 61, $F = Nf$, applies.

The methods of calculating cutting time for the basic processes of turning, milling, and drilling have been demonstrated to show their rational basis. The same procedure is followed for any metal-cutting process, with modifications to conform to its inherent characteristics.

Problem 27. Estimate the machine time for the piece of Fig. 75.

Problem 28. Estimate the machine time for the piece of Fig. 76.

Problem 29. A H.S.S. face-milling cutter, 10 in. in diameter, has 24 teeth. It is used to mill a surface 24 in. long by 9 in. wide. Estimate the machine time for rough and finish milling, if the workpiece material is (a) Cast iron, (b) SAE X1315 steel, (c) SAE 1020 steel, (d) SAE 3150 steel.

Problem 30. A face mill, 12 in. in diameter, has 18 teeth of cemented carbide. It is used to mill a surface 12 in. long by 10 in. wide. Estimate the machine time for rough and finish milling, if the workpiece material is (a) Cast iron, (b) SAE X1315 steel, (c) SAE 1020 steel, (d) SAE 3150 steel.

Problem 31. An H.S.S. side-milling cutter is used to cut the groove in the piece of Fig. 221. The groove is 1 in. wide and $\frac{3}{4}$ in. deep and passes through the entire length of the piece of 7 in. The cutter is 6 in. in diameter and has 16 teeth. One cut is taken. Estimate the machine time, if the material is (a) Cast iron, (b) SAE X1315 steel, (c) SAE 1030 steel.

Problem 32. An H.S.S. drill is to make a hole through a piece of cast iron, 1 in. thick. Estimate the machining time, if the diameter of the drill is (a) $\frac{1}{16}$ in., (b) $\frac{3}{16}$ in., (c) $\frac{1}{2}$ in., (d) 1 in.

Relative importance of man time and machine time. It is significant to observe that as manufacturing equipment becomes more automatic, machine time becomes a larger factor and man time of less importance. If a standard design or practice is followed for semiautomatic equipment, the operator is given little alternative but to follow a prescribed course, and forecasts of results are consequently more apparent. On many types of jobs the man time can be made to approach a constant value. As for fully automatic machinery, the elements of a cycle of an operation are predetermined by the characteristics of the machine. The machining time for a piece produced on an automatic screw machine, for instance, is determined by the movements and speeds of the machine.

Maintenance and down time

No estimate can pretend to predict the actual time that will be taken in the factory for doing a job. What can be and is achieved is an average conformity to real performance over a space of time. Unpredictable contingencies may occur in any project, causing it to deviate from its predicted course. If everything goes well, expectations may be exceeded, but quite often the reverse is the case. Smooth performance is the exception rather than the rule in most plants. The operator may have to wait for materials or tools. Breakdowns or mishaps to machines or tools may be experienced. Evidently, these circumstances cannot be foretold in any one estimate. However, their statistical prevalence can be determined and sufficient adjustment made in each estimate to compensate for them over a period of time.

It is common practice to apply a general performance factor, R, to estimates, on the basis that:

$$R = \frac{T_A}{T_E} \tag{63}$$

when

T_A = time taken for a number of specific jobs, and
T_E = time estimated for the same jobs.

Sufficient jobs are chosen over a long enough period to be representative. Subsequent estimates are then increased by multiplying them by the factor, which can be recalculated and revised as desirable to conform to changing conditions. Studies in various plants have revealed a performance factor of between 1.10 and 1.70.

EXAMPLE 13: Estimate the direct labor cost of 10 studs, shown in Fig. 74, on a 16-in. engine lathe.

1. *Calculation of machine time elements*

a. Turn to 0.900-in. diameter by $2\frac{7}{16}$ in. long.
For cemented carbide tools, use 312 s.f.p.m.
For $1\frac{1}{2}$-in. original diameter speed is approximately 800 r.p.m.
Feed = 0.015 in. per revolution for depth of cut of 0.30 in.
From Fig. 83, unit time = 0.08 min/in.
Cutting time = 2.437 × 0.08 = 0.20 min.

b. Turn to 0.650-in. diameter by $1\frac{11}{16}$ in. long.
Feed = 0.025 in. per revolution.
r.p.m. = 1200, assumed maximum for lathe.
Unit time = 0.03 min/in.
Cut time = 1.69 × 0.03 = 0.05 min.

c. Finish turn $0.874\,{}^{+0.000}_{-0.002}$ in. diameter.
Feed = 0.010 in. per revolution.
r.p.m. = 1200.
Unit time = 0.08 min/in.
Cut time = 0.75 × 0.08 = 0.06 min.

d. Finish face shoulder under head.
Feed = 0.007 in. per revolution.
r.p.m. = 225.
Length of tool travel $\dfrac{1.5 - 0.88}{2} = 0.31$ in.
Unit time = 0.63 min.
Cut time = 0.31 × 0.63 = 0.20 min.

e. Finish turn $0.625\,{}^{+0.001}_{-0.000}$-in. diameter.
Assume 1-in. length.
Feed = 0.010 in. per revolution.
r.p.m. = 1200.
Cut time = 1 × 0.08 = 0.08 min.

f. Finish-turn $\frac{1}{2}$-in. thread diameter.
Cut time = $\frac{3}{4}$ × 0.08 = 0.06 min.

g. Form 45° chamfer on head.
Use H.S.S. tool at 90 s.f.p.m.
Feed at 0.007 in. per revolution.
Depth of cut $\frac{3}{16}$ in. to allow for approximate positioning of tool.
Unit time = 0.63 min/in.
Cut time = 0.19 × 0.63 = 0.12 min.

h. Face shoulder to $0.750\,{}^{+0.005}_{-0.000}$ dimension and cut groove.
Feed at 0.007 in. per revolution.
Speed of 90 s.f.p.m.
Length of cut $= \dfrac{0.88 - 0.60}{2} = 0.14$ in.
Unit time = 0.37 min/in.
Cut time = 0.37 × 0.14 = 0.06 min.

i. Face shoulder and cut thread relief.
Unit time = 0.37 min/in.
Length of cut $= \frac{0.63 \times 0.43}{2} = 0.10$ in.
Cut time $= 0.37 \times 0.10 = 0.04$ min.

j. Center drill end.
Length of cut $\frac{5}{16}$ in.
Speed at 1200 r.p.m., maximum of lathe.
Feed = 0.004 in per revolution
Unit time = 0.21 min/in.
Cut time $= 0.32 \times 0.21 = 0.07$ min.

k. Cut thread.
Cut speed = 49 s.f.p.m. or 375 r.p.m.
Travel $= \frac{3}{4} \times 13 = 9.75$ revolutions.
Time for one cut $= \frac{9.75}{375} = 0.036$ min per cut.
Assume average of 0.005 min per cut.
Depth of cut = 0.042 in.
9 cuts required on thread.

l. Cut off.
H.S.S. tool at 90 s.f.p.m. = 225 r.p.m.
Feed = 0.007 in. per revolution.
Length of travel = $\frac{3}{4}$ in.
Unit time = 0.63.
Cut time $= 0.63 \times 0.75 = 0.48$ min.

2.	*Man and machine elements per piece*	*Minutes*
1.	Release universal chuck, move material out by hand, scale for proper amount of stock and secure material in chuck for work	0.450
2.	Remove center and install drill chuck and center drill in tailstock	0.150
3.	Advance tool to work	0.100
4.	Center drill	0.070
5.	Withdraw tool	0.100
6.	Remove drill chuck and insert center	0.150
7.	Advance center to work	0.100
8.	Install tool bit in holder and adjust	0.500
9.	Move cross slide into position, set tool to depth, advance tool to work, engage feed	0.200
10.	Trial cut ¼ in. long (0.08 × 0.25)	0.020
11.	Mike diameter	0.200
12.	Back tool from work, set to proper depth by micrometer dial, advance tool to work, engage feed	0.300
13.	Rough turn 0.900-in. diameter	0.200
14.	Back tool from work, set to proper depth by dial, advance to work, engage feed	0.300
15.	Rough turn 0.650-in. diameter	0.050
16.	Mike diameter	0.200
17.	Back tool from work, set to depth by dial, advance to work, engage feed	0.300

		Minutes
18.	Trial-cut ½-in. diameter × ¼-in. long.	
19.	Mike diameter	0.200
20.	Back tool from work, set to depth, advance tool to work, engage, feed	0.300
21.	Finish turn ½-in. thread diameter	0.060
22.	Mike diameter	0.200
23.	Back up tool, set by dial, engage feed	0.300
24.	Trial cut ¼ in. long	0.020
25.	Back up tool, mike, make adjustment, advance tool to work, engage feed	0.400
26.	Semi-finish turn 0.625-in. diameter	0.080
27.	Back up tool, mike, make adjustment, advance tool to work, engage feed	0.400
28.	Finish-turn $0.625^{+0.001}_{-0.000}$-in. diameter	0.080
29.	Mike	0.200
30.	Back up tool, adjust by dial, engage feed	0.300
31.	Trial cut ¼-in. long	0.020
32.	Back tool from work, mike, set proper tool depth, advance tool to work, engage feed	0.400
33.	Finish turn $0.874^{+0.000}_{-0.002}$-in. diameter	0.060
34.	Mike	0.200
35.	Change tool in tool holder, set to proper angle for cut	0.400
36.	Move cross slide into position, advance tool to work	0.200
37.	Form cut for 45° chamfer on head	0.120
38.	Back from work, position tool in clear	0.100
39.	Change tool in post, set in position	0.400
40.	Advance cross slide tool, scale for proper position of cut, engage feed	0.200
41.	Face shoulder under head	0.200
42.	Form $\frac{1}{32}$ radius and blend with 0.874-in. diameter	0.200
43.	Position tool and engage feed	0.150
44.	Rough-face shoulder	0.060
45.	Back tool from work and mike	0.300
46.	Set tool to proper depth, advance to work, engage feed	0.400
47.	Finish-face to $0.750^{+0.005}_{-0.000}$-in. dimension and cut groove	0.060
48.	Mike	0.200
49.	Position tool, scale for proper position of cut, engage feed	0.200
50.	Face shoulder and form thread relief	0.040
51.	Back tool into clear	0.100
52.	Change tool and set to proper position	0.400
53.	Advance tool to work	0.100
54.	Chamfer thread end	0.040
55.	Back tool into clear	0.100
56.	Change tool, set in proper position, and secure	0.400
57.	Position tool, set proper micrometer depth, start machine, engage feed at proper lead	0.200
58.	Nine cuts on thread	0.270
59.	Eight settings of tool at 0.150 each	1.200
60.	Position cross slide into clear, 2 × 0.100	0.200

	Minutes
61. Blow thread clean, 2 × 0.080	0.160
62. Check with gage, 2 × 0.300	0.600
63. Clean up threads	0.400
64. Change tool in tool post and check	0.400
65. Scale for cut, position tool to work	0.150
66. Break 4 edges with file	0.200
67. Cut off	0.480
Total element time	15.260
Allowances:	
a. Tool sharpen	3.000
b. Personal, 5%	0.760
c. Fatigue, 15%	2.250
Man and machine time each	21.310
For 10 pieces	213.10
Setup time.	
1. Make up time slip and check in on job	1.000
2. Study drawing	1.000
3. Trip to tool crib	5.000
4. Allowance for 10 tools handled	6.000
5. Install three-jaw chuck on spindle	2.000
6. Install tool post on cross slide	0.400
7. Release compound rest, swing into proper position, and secure	0.400
8. Install drill chuck in taper sleeve	0.500
9. Position tail stock and lock to ways	0.200
10. Deliver first piece to inspector	0.700
11. Sign out on completed job	1.000
12. Separate drill chuck from adapter sleeve	0.250
13. Remove cutting tools and store	0.250
14. Remove toolholders and store	0.250
15. Remove tool post and store	0.350
16. Clean measuring instruments and return	0.250
17. Remove chuck	1.000
18. Remove center from tailstock	0.300
	20.850
Total time for 10 pieces	213.10 20.85
	233.95

If the performance factor is 1.25, then the estimated time should be

$$233.95 \times 1.25 = 292.44 \text{ min.}$$
$$= 4.88 \text{ hours}$$

At $1.75 per hour, direct labor cost is

$$\$1.75 \times 4.88 = \$8.54.$$

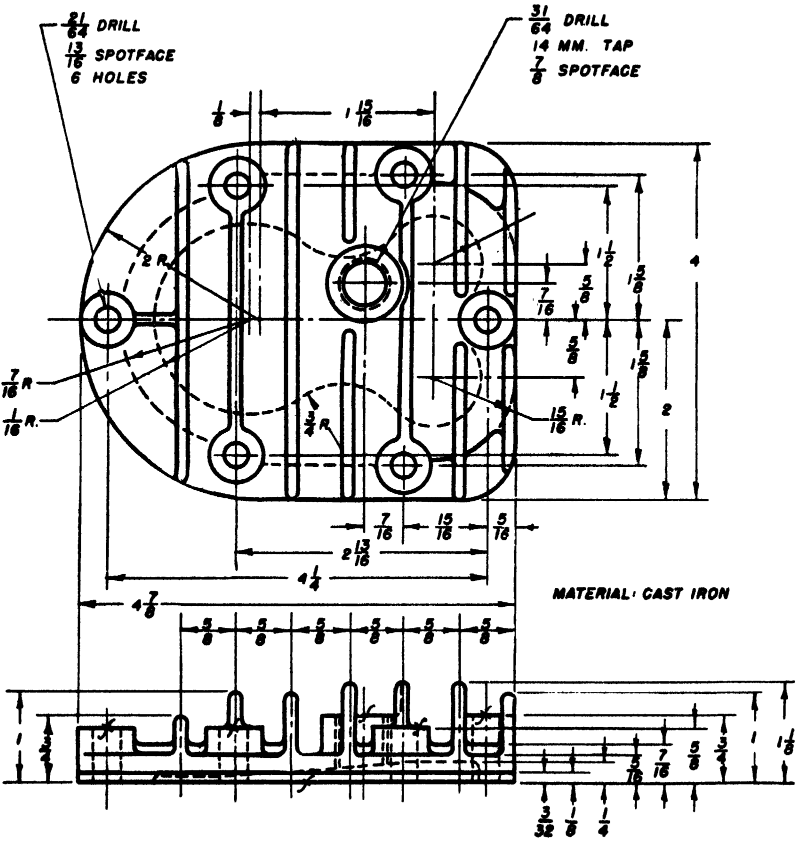
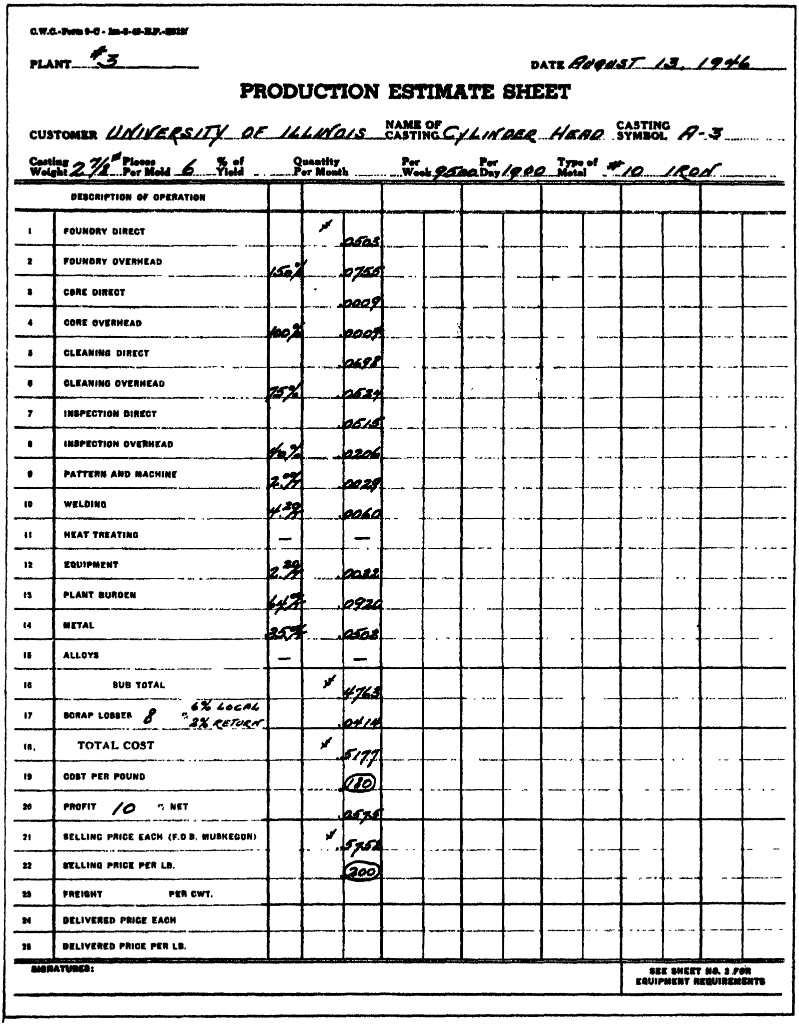


Fig. 84. A cylinder head.

Estimate forms

The sample estimate of Fig. 85 shows the actual procedure of arriving at a price for a casting in one of the country's leading foundries. On sheet No. 1 of the estimate, the pertinent items of cost are entered and totalled. These include auxiliary services, material, labor, and overhead. Sheets 2, 3, 4, and 5 show how the figures for the direct items are obtained from the elements of the operations.

The sample tool estimate sheet of Fig. 86 indicates the procedure followed in one tool shop for estimating the cost of tools.



C.W.C.-Form 9-C - 1m-8-45-H.P.-[illegible]

PLANT #3

DATE AUGUST 13, 1946

PRODUCTION ESTIMATE SHEET

CUSTOMER UNIVERSITY OF ILLINOIS

NAME OF CASTING CYLINDER HEAD

CASTING SYMBOL A-3

Casting Weight 2 7/8 # Pieces Per Mold 6 % of Yield Quantity Per Month Per Week 9500 Per Day 1900 Type of Metal #10 IRON

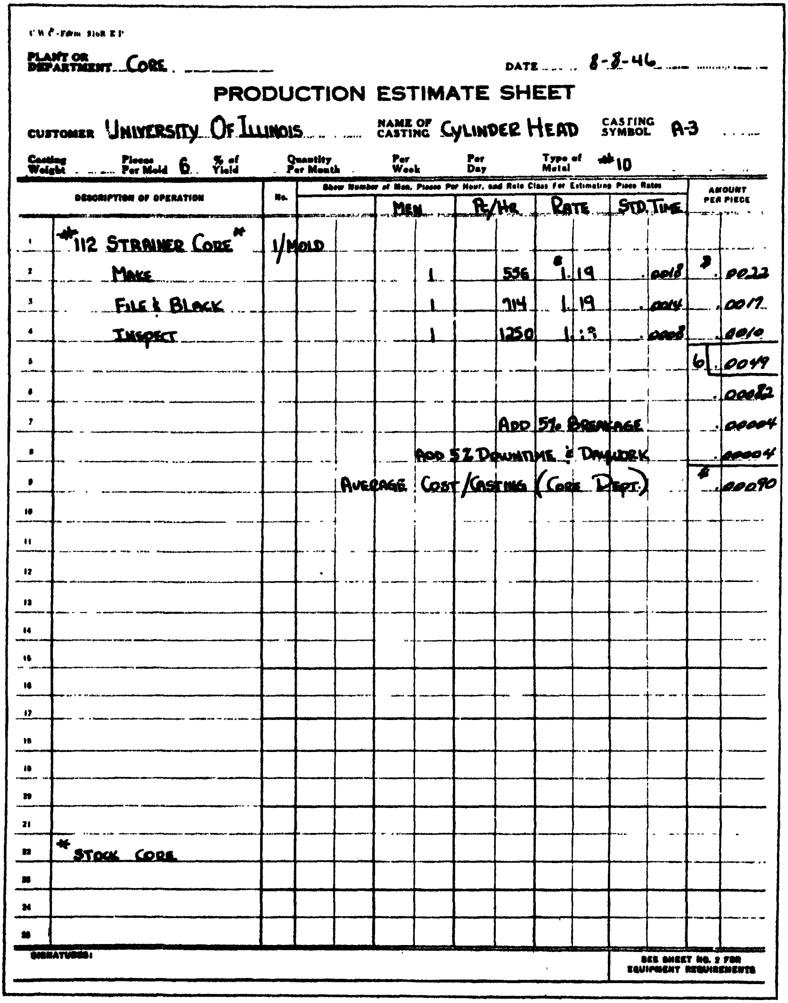
	DESCRIPTION OF OPERATION			
1	FOUNDRY DIRECT		✓	.0505
2	FOUNDRY OVERHEAD	150%		.0755
3	CORE DIRECT			.0009
4	CORE OVERHEAD	100%		.0009
5	CLEANING DIRECT			.0698
6	CLEANING OVERHEAD	75%		.0524
7	INSPECTION DIRECT			.0515
8	INSPECTION OVERHEAD	40%		.0206
9	PATTERN AND MACHINE	2.9%		.0029
10	WELDING	4.29%		.0060
11	HEAT TREATING	—		—
12	EQUIPMENT	2.29%		.0032
13	PLANT BURDEN	64%		.0920
14	METAL	35%		.0508
15	ALLOYS	—		—
16	SUB TOTAL		✓	.4763
17	SCRAP LOSSES 8 % 6% LOCAL 2% RETURN			.0414
18	TOTAL COST		✓	.5177
19	COST PER POUND			.180
20	PROFIT 10 % NET			.0575
21	SELLING PRICE EACH (F.O.B. MUSKEGON)		✓	.5752
22	SELLING PRICE PER LB.			.200
23	FREIGHT PER CWT.			
24	DELIVERED PRICE EACH			
25	DELIVERED PRICE PER LB.			

SIGNATURES:

SEE SHEET NO. 2 FOR EQUIPMENT REQUIREMENTS

SHEET NO. 1

Fig. 85. Estimate of cost of casting cylinder head of Fig. 84. (Courtesy Campbell, Wyant, & Cannon Foundry Co., Muskegon, Mich.)



C W C-Form 510R EP

PLANT OR DEPARTMENT Core

DATE 8-8-46

PRODUCTION ESTIMATE SHEET

CUSTOMER University Of Illinois NAME OF CASTING Cylinder Head CASTING SYMBOL A-3

Casting Weight Pieces Per Mold 6 % of Yield Quantity Per Month Per Week Per Day Type of Metal #10

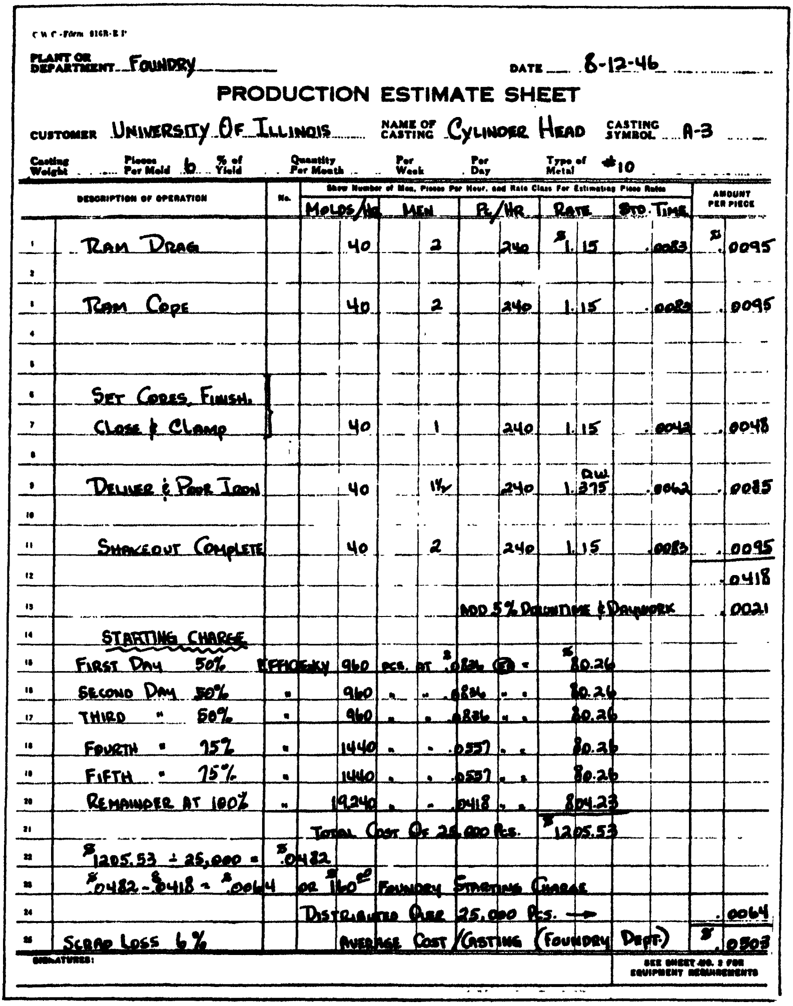
	Description of Operation	No.	Show Number of Men, Pieces Per Hour, and Rate Class For Estimating Piece Rates					Amount Per Piece
				Men	Pc/Hr	Rate	Std. Time	
1	*112 Strainer Core*	1/Mold						
2	Make			1	556	$1.19	.0018	$.0022
3	File & Black			1	714	1.19	.0014	.0017
4	Inspect			1	1250	1.19	.0008	.0010
5								6 | .0049
6								.00082
7					Add 5% Breakage			.00004
8				Add 5% Downtime & Daywork				.00004
9			Average Cost/Casting (Core Dept.)					$.00090
10								
11								
12								
13								
14								
15								
16								
17								
18								
19								
20								
21								
22	*Stock Core							
23								
24								
25								

SIGNATURES:

SEE SHEET NO. 2 FOR EQUIPMENT REQUIREMENTS

Sheet No. 2

Fig. 85 (continued)



C.W.C.-Form 816R-E.P.

PLANT OR DEPARTMENT Foundry DATE 8-12-46

PRODUCTION ESTIMATE SHEET

CUSTOMER University Of Illinois NAME OF CASTING Cylinder Head CASTING SYMBOL A-3

Casting Weight Pieces Per Mold 6 % of Yield Quantity Per Month Per Week Per Day Type of Metal #10

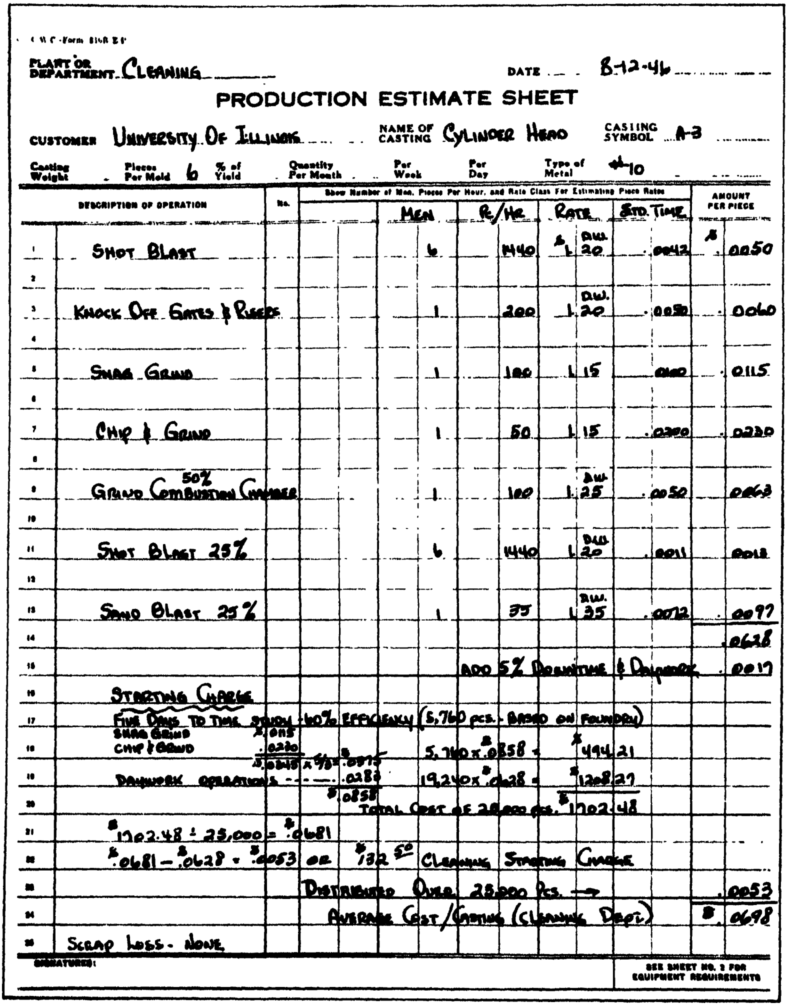
DESCRIPTION OF OPERATION	No.	Show Number of Men, Pieces Per Hour, and Rate Class For Estimating Piece Rates					AMOUNT PER PIECE
		Molds/Hr.	Men	Pc/Hr.	Rate	Std. Time	
Ram Drag		40	2	240	$1.15	.0083	$.0095
Ram Cope		40	2	240	1.15	.0083	.0095
Set Cores, Finish, Close & Clamp		40	1	240	1.15	.0042	.0048
Deliver & Pour Iron		40	1½	240	D.W. 1.375	.0062	.0085
Shakeout Complete		40	2	240	1.15	.0083	.0095
							.0418
				Add 5% Downtime & Daywork			.0021
Starting Charge							
First Day 50%	Efficiency	960 pcs.	at	$.0836	@ =	$80.26	
Second Day 50%	"	960	"	" .0836	" "	80.26	
Third " 50%	"	960	"	" .0836	" "	80.26	
Fourth " 75%	"	1440	"	" .0557	" "	80.26	
Fifth " 75%	"	1440	"	" .0557	" "	80.26	
Remainder at 100%	"	19,240	"	" .0418	" "	804.23	
		Total Cost Of 25,000 Pcs.				$1205.53	
$1205.53 ÷ 25,000 =	$.0482						
$.0482 - $.0418 = $.0064	or $160.00	Foundry Starting Charge					
		Distributed Over 25,000 Pcs. →					.0064
Scrap Loss 6%			Average Cost/Casting (Foundry Dept.)				$.0503

SIGNATURES:

SEE SHEET NO. 2 FOR EQUIPMENT REQUIREMENTS

Sheet No. 3

Fig. 85 (continued)



C.W.C.-Form 1168 E P

PLANT OR DEPARTMENT Cleaning DATE 8-12-46

PRODUCTION ESTIMATE SHEET

CUSTOMER University Of Illinois NAME OF CASTING Cylinder Head CASTING SYMBOL A-3

Casting Weight Pieces Per Mold 6 % of Yield Quantity Per Month Per Week Per Day Type of Metal #10

	DESCRIPTION OF OPERATION	No.	Show Number of Men, Pieces Per Hour, and Rate Class For Estimating Piece Rates						AMOUNT PER PIECE
					Men	Pc/Hr	Rate	Std. Time	
1	Shot Blast				6	1440	$1.20 D.W.	.0042	$ .0050
2									
3	Knock Off Gates & Risers				1	200	1.20 D.W.	.0050	.0060
4									
5	Snag Grind				1	100	1.15	.0100	.0115
6									
7	Chip & Grind				1	50	1.15	.0200	.0230
8									
9	Grind Combustion Chamber 50%				1	100	1.25 D.W.	.0050	.0063
10									
11	Shot Blast 25%				6	1440	1.20 D.W.	.0011	.0013
12									
13	Sand Blast 25%				1	35	1.35 D.W.	.0072	.0097
14									.0628
15					Add 5% Downtime & Daywork				.0017

16 Starting Charge

17 Five Days to Time Study - 60% Efficiency (5,760 pcs. - Based on Foundry)

18 Snag Grind $.0115
Chip & Grind .0230 5,760 x $.0858 = $494.21

19 $.0345 x 5/3 = $.0575
Daywork Operations ---- .0283 19,240 x $.0628 = $1208.27

20 $.0858 Total Cost of 25,000 pcs. $1702.48

21 $1702.48 ÷ 25,000 = $.0681

22 $.0681 – $.0628 = $.0053 or $\$132^{50}$ Cleaning Starting Charge

23 Distributed Over 25,000 Pcs. → .0053

24 Average Cost/Casting (Cleaning Dept.) $ .0698

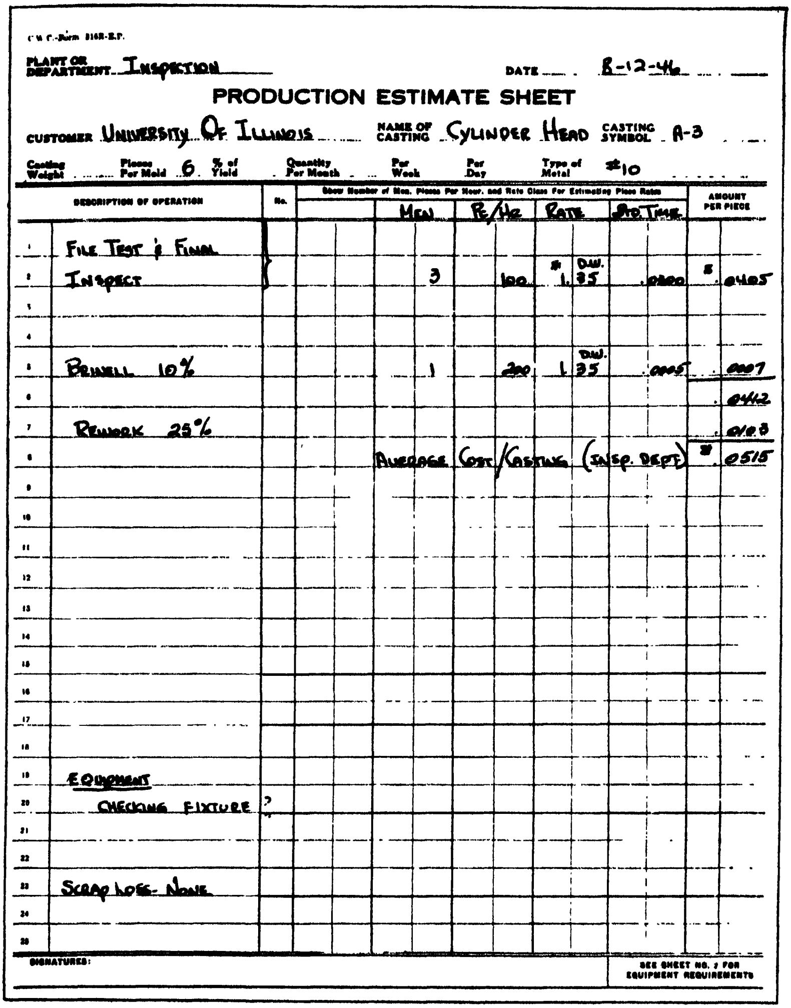
25 Scrap Loss - None

SIGNATURES:

SEE SHEET NO. 2 FOR EQUIPMENT REQUIREMENTS

Sheet No. 4

Fig. 85 (continued)



C M C.-Form 316R-E.P.

PLANT OR DEPARTMENT Inspection DATE 8-12-46

PRODUCTION ESTIMATE SHEET

CUSTOMER University Of Illinois NAME OF CASTING Cylinder Head CASTING SYMBOL A-3

Casting Weight .... Pieces Per Mold 6 % of Yield .... Quantity Per Month .... Per Week .... Per Day .... Type of Metal #10

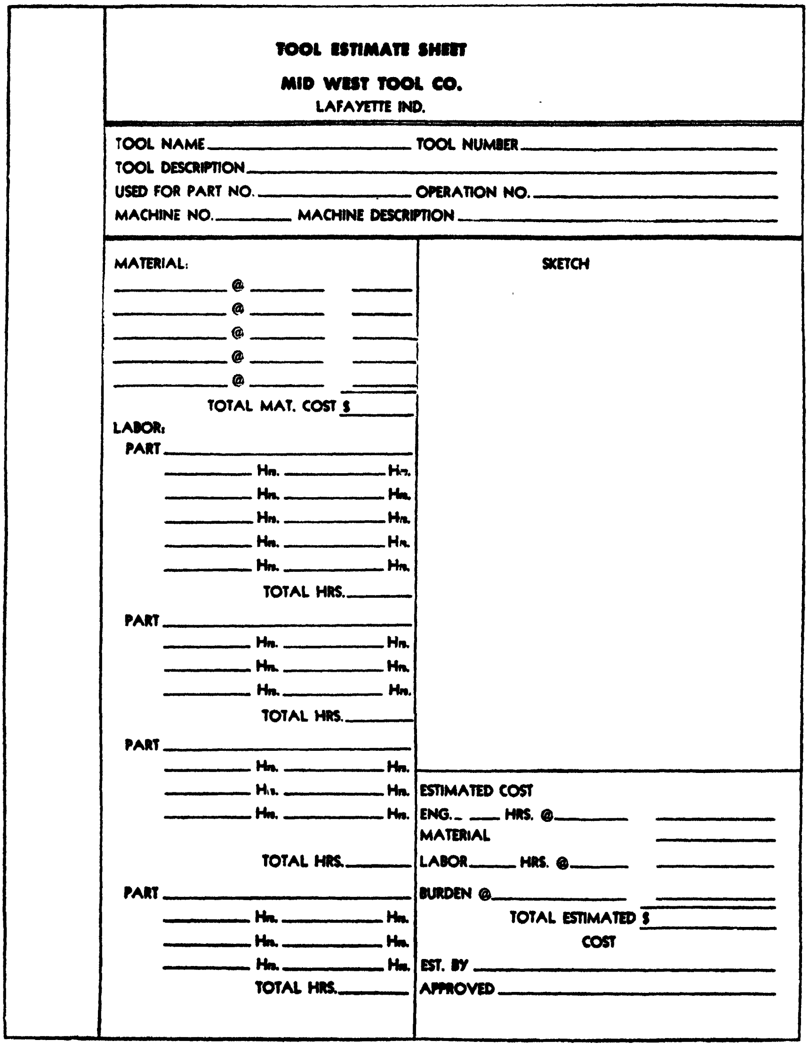
	DESCRIPTION OF OPERATION	No.	Show Number of Men, Pieces Per Hour, and Rate Class For Estimating Piece Rates					AMOUNT PER PIECE
				Men	Pc/Hr	Rate	Std. Time	
1	File Test & Final							
2	Inspect			3	100	$ 1.35 D.W.	.0200	$ .0405
3								
4								
5	Brinell 10%			1	200	1.35 D.W.	.0005	.0007
6								.0412
7	Rework 25%							.0103
8				Average Cost/Casting (Insp. Dept)				$ .0515
9								
10								
11								
12								
13								
14								
15								
16								
17								
18								
19	Equipment							
20	Checking Fixture	?						
21								
22								
23	Scrap Loss- None							
24								
25								

SIGNATURES:

SEE SHEET NO. 1 FOR EQUIPMENT REQUIREMENTS

SHEET NO. 5

Fig. 85 (concluded)



TOOL ESTIMATE SHEET
MID WEST TOOL CO.
LAFAYETTE IND.

TOOL NAME ______ TOOL NUMBER ______
TOOL DESCRIPTION ______
USED FOR PART NO. ______ OPERATION NO. ______
MACHINE NO. ______ MACHINE DESCRIPTION ______

MATERIAL:
______ @ ______ ______
______ @ ______ ______
______ @ ______ ______
______ @ ______ ______
______ @ ______ ______
TOTAL MAT. COST $ ______

LABOR:
PART ______
______ Hrs. ______ Hrs.
______ Hrs. ______ Hrs.
______ Hrs. ______ Hrs.
______ Hrs. ______ Hrs.
______ Hrs. ______ Hrs.
TOTAL HRS. ______

PART ______
______ Hrs. ______ Hrs.
______ Hrs. ______ Hrs.
______ Hrs. ______ Hrs.
TOTAL HRS. ______

PART ______
______ Hrs. ______ Hrs.
______ Hrs. ______ Hrs.
______ Hrs. ______ Hrs.
TOTAL HRS. ______

PART ______
______ Hrs. ______ Hrs.
______ Hrs. ______ Hrs.
______ Hrs. ______ Hrs.
TOTAL HRS. ______

SKETCH

ESTIMATED COST
ENG. ______ HRS. @ ______ ______
MATERIAL ______
LABOR ______ HRS. @ ______ ______
BURDEN @ ______ ______
TOTAL ESTIMATED COST $ ______
EST. BY ______
APPROVED ______

Fig. 86. Sample tool-estimate sheet. (From Owen, *Introduction to Tool Engineering*, p. 140, Prentice-Hall, 1948.)

SUMMARY

Estimates of cost are necessary for valid economic comparisons, for setting the selling prices of many articles, and for justifying proposed methods and tooling. Generally, the cost of making an article must be estimated before any other steps are taken to produce it.

Cost estimates must be built on an understanding of:

1. The characteristics of materials.
2. The methods and techniques of manufacturing.
3. Ways of ascertaining and recording costs.
4. The fundamentals of time and motion study.
5. The principles of tooling.
6. The ways of comparing alternate methods.

The fundamental approach to estimating is to break a job into parts that are easily evaluated by calculations or comparisons. The extent to which a task is divided varies. In some cases over-all comparisons are in order, but should always be carefully scrutinized. At the other extreme, operations may be divided into small elements.

The complete estimate of the cost of a manufactured article is composed of the following items:

1. The cost of the auxiliary services, if they are allocated separately to the individual job. In many cases these services are included in the overhead and do not appear as items of the estimate. In other cases, only part of them may be estimated specifically. Special patterns and tools applicable to only one job are normally charged to that job alone.
2. The material cost.
3. The cost of direct labor.
4. Overhead, often as a percentage of direct labor, but also on other bases where they are more applicable.

Where an auxiliary service is itemized separately, its cost is found by multiplying the estimated direct time for it by a rate which includes functions related to it but difficult to distribute exactly. The direct time for many auxiliary services can only be estimated from comparison with similar past performance.

There are four steps in estimating the material cost of an article. They are:

1. Determine the rough size of the piece.
2. Calculate the rough weight.
3. Add losses not related to the individual pieces.
4. Multiply the quantity of material by the base price.

Material costs for tools may include those for standard details that are purchased.

The direct labor time of a productive operation is made up of:

1. Setup time.
2. Man or handling time.
3. Machine or cutting time.
4. Maintenance or down time.

The man and machine times for an operation may be found by breaking the operation into suitable elements. Setup time is also made up of elements, but is normally treated separately.

Man time can most accurately be found by synthesis. Typical handling elements for all types of machines are measured and recorded. From these, the elements needed for a specific job can be chosen and added together. To the measured elements, allowances are added for personal needs, fatigue, tool sharpening, and checking.

Machine time can be calculated from the basic equation of:

$$\text{The time for a cut in minutes} = \frac{\text{length of travel of the tool or work}}{\text{feed in inches per minute.}}$$

The length of travel has three parts, which are: (1) the distance over which the tool takes a full cut, (2) overtravel, (3) approach.

The feed in inches per minute is derived from the bite taken by the tool. General specifications for speeds and feeds that will stand up under competitive conditions are difficult to forecast. Judgment must be used by an estimator to approximate the speeds and feeds likely to be used on a job.

To make up for uncertainties, it is common practice to apply a general performance factor to estimates to adjust them to the realities of experience.

Example 14: Estimate the total cost of 10 studs like the one shown in Fig. 74. The engineering rate is $2.25 and ½ hour is needed for making the drawing and preparing prints for the shop.

Overhead rate is 1.5. Thus, the pertinent items are:

Engineering, ½ × 2.25	$ 1.13
Material (from Example 11)	1.72
Direct labor (from Example 13)	8.54
Overhead, 8.54 × 1.5	12.81
Total cost	$24.20

To the total cost must be added the desired profits, selling expense, etc., to obtain the selling price of the article. Sometimes a factor for these items is furnished by the management.

Problem 33. Estimate the total cost to make 5 studs like that shown in Fig. 75. The direct labor dollar overhead rate is 1.5. One-half hour of engineering at $2.50 per hour is required. The direct labor cost is $1.65.

Problem 34. Estimate the cost to make 25 push rod blanks like that shown in Fig. 76. The direct labor dollar overhead rate is 1.5. The direct labor cost is $1.65.

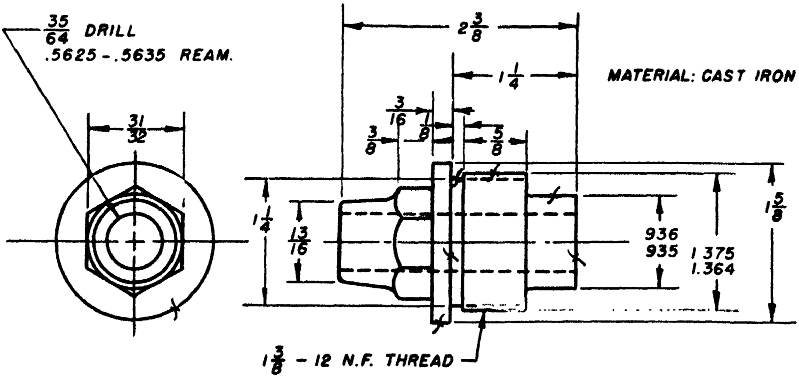


Fig. 87. A valve push rod guide.

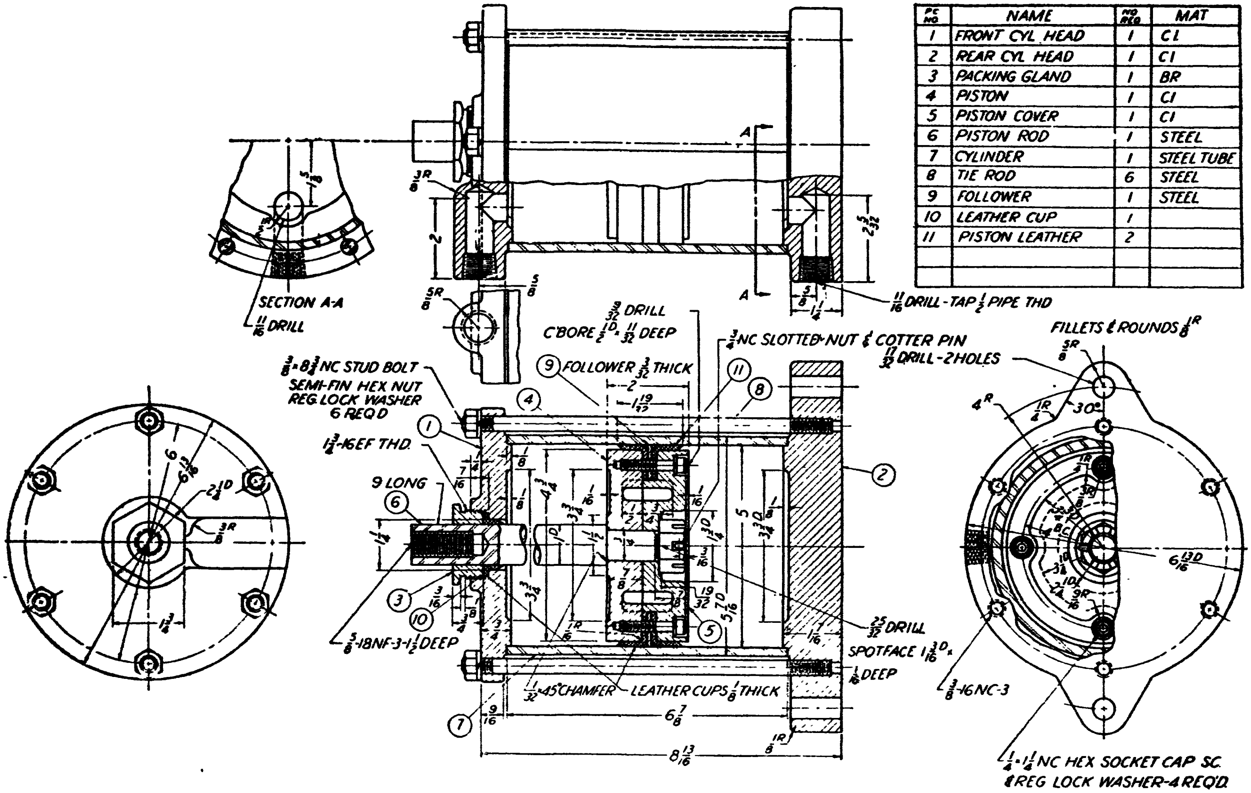
Problem 35. Estimate the cost for 12 valve push rod guides shown in Fig. 87. The castings are obtainable for 20 cents per pound. The direct labor cost is $1.65. The direct labor dollar overhead rate is 1.5.

Problem 36. Estimate the time for turning on a lathe the parts for one air cylinder shown in Fig. 88. Include time for setup, handling and cutting. Add appropriate allowances.

QUESTIONS

1. For what purposes are cost estimates needed?

2. What qualifications must an engineer have to be able to make competent estimates?



PC NO	NAME	NO REQ	MAT
1	FRONT CYL HEAD	1	CI
2	REAR CYL HEAD	1	CI
3	PACKING GLAND	1	BR
4	PISTON	1	CI
5	PISTON COVER	1	CI
6	PISTON ROD	1	STEEL
7	CYLINDER	1	STEEL TUBE
8	TIE ROD	6	STEEL
9	FOLLOWER	1	STEEL
10	LEATHER CUP	1	
11	PISTON LEATHER	2	

Fig. 88. Air cylinder. (From Luzadder, *Fundamentals of Engineering Drawing*, p. 339, Prentice-Hall, 1946.)

3. What general principle describes the basis of all cost estimating?

4. What are some of the precautions that must be taken in using over-all comparisons as bases for estimates?

5. How may the functions necessary to produce an article be classified for estimating?

6. What determines the principal items of an estimate?

7. In general, how are auxiliary services estimated? Are all auxiliary functions treated in the same way? Why?

8. When is the value of material a high percentage of the cost of a job, and when is it low?

9. What factors should be considered for material cost?

10. For a piece made from barstock, how is the total amount of raw material calculated?

11. How much material is needed for a stamping?

12. How is the amount of material needed for a casting estimated?

13. Give a summary of the general procedure for estimating material cost.

14. Into what four parts may any production task be divided?

15. How are operation elements used in estimating?

16. Of what significance to estimating is the fact that there is usually a definite relation between the time value of an element and its variable conditions?

17. What is setup time? Should it be treated as a separate entity for most operations? Why?

18. What is man time? What is machine time?

19. List the elements for typical operations on the following machines: (a) milling machine, (b) turret lathe, (c) gear hobbing machine, (d) radial drill (to drill 2 holes).

20. How are time values for nonmachining elements ascertained?

21. Why must allowances be added to recorded values of man-time elements?

22. For what considerations are allowances added to man-time elements?

23. What conditions determine fatigue allowance? What are typical fatigue allowances for various conditions?

24. How is the allowance for tool sharpening related to tool life?

25. What two considerations determine checking allowance? What factors influence each of these considerations?

26. What is the fundamental relationship on which all machine time calculations are based?

27. What three distances make up the total length of a cut?

28. What is overtravel?

29. What is approach?

30. Can general recommendations be made for speeds and feeds to meet competitive conditions? Why?

31. What conditions influence the proportion of man time to the total time of an operation?

32. Why is it common practice to apply a general performance factor to estimates? How is that factor obtained?

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6 SHORT CUTS AND VARIATIONS IN ESTIMATING

SHORT CUTS IN ESTIMATING

Reasons for simple methods

An evident disadvantage of estimating by synthesis, as described in Chap. 5, is its tediousness and costliness. In spite of this, it has an accepted place in industry, particularly for large quantities, because it is the only means by which the most accurate results can be obtained. But there are many cases where attention to details is superfluous. If only one or a few items of a kind are to be made, error in their unit estimated cost is not as serious as for many parts. Preliminary estimates or surveys do not normally call for as precise statements as those upon which actual contracts are made. Furthermore, in a manufacturing plant the facilities devoted to regular production probably are not used for making special items and thus the applicable factors for the two forms of fabrication are usually different. For those estimates in which more laxity can be tolerated in view of easier preparation, simpler methods than synthesis have been developed.

Approximate factors

One method of approximation is to determine factors from actual performance to be multiplied by calculated machine time to give an estimate of over-all time. As an example, if the calculated machine time for a lathe, planer, shaper, miller, or boring mill, using high-speed steel tools or grinders using conventional abrasives, is multiplied by four, a surprisingly close approximation will be obtained to the total time needed to produce one piece of average accuracy. If cemented-carbide tools are used, providing a lower cutting time, the factor must be proportionately higher. For small tolerances, more exacting adjustments and repeated cuts will be necessary, and a larger factor must be used. For reasonable reliability, these factors must be based upon the conditions prevalent in the plant for which they are used and must be applied with discretion.

One tool engineer found in his plant that the average run of jigs and fixtures took about the same amount of time for fabrication and assembly as for designing and detailing. For special tools and machines, it will often be found that the time for machining the parts or details will be about the same as for fitting and assembling them. None of these relationships or factors can be assumed to apply to all plants or even to all jobs in any one plant. They are cited to demonstrate what the engineer can arrive at through study and experience for his particular purposes. His success in using such short cuts will always depend upon the judgment he is able to exercise in choosing the circumstances that dictate the proper factors for any particular case and indicate when not to apply a certain factor.

Approximate formulas

In many cases approximate formulas can be developed and applied with good results. As an instance, *for external-center-type cylindrical grinding* of pieces over which the wheel must be traversed, the following formula has been used for roughing cuts.[1]

$$T = \frac{L \times S \times d}{2 \times W \times D \times C} \tag{64}$$

where

T = machine time of grinding, in minutes,
L = length of surface ground, in inches,
S = stock on diameter to be removed, in inches,
d = diameter of surface, in inches,
W = width of face of grinding wheel, in inches,
D = depth of cut per pass, in inches (0.001 to 0.004 in. for rough cut and 0.0002 to 0.002 in. for finishing),
C = surface speed of work piece in feet per minute (30 f.p.m. for tough or hard materials, 50 f.p.m. for mild steels, and 75 f.p.m. for soft materials such as aluminum or brass).

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[1] W. A. Nordhoff, *Machine Shop Estimating*, page 343. New York: McGraw-Hill Book Co., Inc., 1947.

In practice this formula has been reported to give reasonable answers in about 75 per cent of the external grinding jobs. It is based on the assumption that the wheel advances a distance $W/2$ for each revolution of the workpiece and the number of revolutions per minute (N) of the workpiece is approximately 4 $C.S./D$, from which the derivation is evident. For finishing, the wheel can be assumed to advance an amount of $W/4$ for each revolution of the workpiece, and

$$T = \frac{L \times S \times d}{W \times D \times C} \tag{65}$$

The *production rate of a punch press operation* is largely determined by the speed of the press in strokes per minute, one piece being produced at each stroke. In addition to the time consumed by the press action, operator time is needed for loading, unloading, locating, and so on. For blanks from strips, it has been found for the large majority of cases that the press is actually working only about 24 min out of an hour with hand-feed of the strips, and about 48 min with roll-feed. On this basis the following expression can be used for labor cost per 1000 blanks:[2]

For hand feed

$$C_H = \frac{L}{0.024N} \tag{66}$$

For roll feed

$$C_R = \frac{L}{0.048N} \tag{67}$$

where

C = labor cost per 1000 blanks, in dollars,
L = hourly labor charge, in dollars,
N = number of press strokes per minute.

If the press to be used is known, the number of strokes per minute (N) can be found from its specifications. Otherwise, the following recommendations[3] have been made for estimating stamping, shaving, and trimming operations:

---

[2] C. W. Hinman, *Die Engineering Layouts and Formulas*, page 148. New York: McGraw-Hill Book Co., Inc., 1943.

[3] Wm. H. Schutt, *Process Engineering*, page 17. New York: McGraw-Hill Book Co., Inc., 1948.

1. 50 to 200 r.p.m. (100 r.p.m. average) for ordinary metal up to ¼ in. thick.
2. 25 to 75 r.p.m. (50 r.p.m. average) for thicknesses over ¼ in. with geared presses.

TOOL ESTIMATING

Comparison with standards

The fact that many types of jigs, fixtures, tools, gages, and dies possess in common certain fundamental details or require certain universally performed operations in their fabrication permits simplification and approximation in estimating their cost with remarkably accurate results. Standardized bushings, in various sizes, for example, are normal components of almost every jig. They can be purchased commercially and their use makes possible immediate appraisal of their cost. For locating and nesting in jigs and fixtures, blocks and pads of various sizes are frequently used, but most of them can be classified essentially into comparatively few groups. Generally, the cost of making blocks of a reasonably similar form varies only with the size, and means can be found to appraise the cost easily of any particular block in a certain category merely by comparing it with the standard. These examples are merely illustrative. The ideas that they represent can be utilized in many other ways.

It should not be inferred that any system of estimating has been devised whereby accurate estimates can be arrived at solely from formulas, charts, or tables. Such forms of information merely serve as convenient tools and must be supplemented by a background of engineering principles and a knowledge of construction and design of the articles considered. The engineer must be able to visualize the machine and hand work necessary for construction of a jig, fixture, or die if he is to realize fully what is required and before he can be certain that any available data are comparable and applicable.

A typical method of tool estimating

In the volume on *Die Designing and Estimating* based on the works of Charles Bohmer and George Dannes,[4] a simple, yet resourceful, method of estimating the common details of the average run of tools and dies is presented. Instead of the time-consuming procedure of estimating the cost of each operation and tool detail individually, this method tabulates all the operations and groups the various details according to their relationship to each other. It takes into account all the factors which determine the cost of a tool, yet treats them in natural combinations. Using a die as an example, the authors offer the following classification of the work to make it:

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[4] Descriptions, tables, and illustrations for this method are reproduced by permission of the publisher, Huebner Publications, Cleveland, Ohio.

Group A—Machining.
  Squaring of blocks—die, punch, punch plate, stripper, etc.
  Grinding before and after hardening.
Group B—Holes.
  Screw and dowel holes.
  All other holes (except perforator or pilot holes).
Group C—Layout.
  Die layout, die opening.
  Location of perforator, etc.
  Inspection.
Group D—Work on die.
  Machining of die opening.
  Finishing of die opening.
  Machining and fitting of punch.
  Opening of punch plate.
  Clearance in stripper and die shoe.
  Stripper slot.
Group E—Accessories.
  Perforators, pilots.
  Perforator and pilot holes in die, punch plate, stripper, and die shoe.
  Knockouts.
  Stops.
  Nests.
  Spring pins and miscellaneous accessories.
Group F.
  Assembling.
  Development.
  Tryout.

These groups include all requirements and are arranged with comparable work in each group rather than in operational sequence. The basis for setting the time of all items in any one group is uniform and the arrangement can save considerable estimating time. Tables of standard work-time can be set up by groups for ready reference. Two specific examples will now be given from *Die Design-*

ing and Estimating, to illustrate the treatment of the various items. These examples have been extracted to convey an understanding of the principles of the method and are not intended to give a complete estimate for any one part.

The several blocks of steel from which the principal details of the die are made must each be machined on six sides to square and true the surfaces to be used as references so that the pieces can be worked

TABLE 4

TIME VALUES FOR SQUARING DIE BLOCKS

		WIDTH IN INCHES														
THICKNESS IN INCHES	3	¼	½	¾	1	2	3	4	5	6	7	7½	8	9	10	11
	2	½	¾	1	2	3	4	5	6	7	8	9	10	11	12	13
	1	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
	½	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
LENGTH IN INCHES	1	.3	.3	.4	.4	.5	.5	.5	.6	.6	.6	.6	.7	.7	.7	.7
	2	.3	.4	.5	.5	.6	.6	.6	.7	.7	.7	.8	.8	.8	.9	.9
	3	.4	.5	.5	.6	.6	.7	.7	.8	.8	.9	.9	1.0	1.0	1.1	1.1
	4	.4	.5	.6	.6	.7	.7	.8	.9	1.0	1.1	1.1	1.3	1.3	1.3	1.4
	5	.5	.6	.6	.7	.8	.8	.9	1.0	1.1	1.2	1.2	1.3	1.4	1.5	1.6
	6	.5	.6	.7	.7	.8	.9	1.0	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8
	7	.5	.6	.7	8	.9	1.0	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	2.0
	8	.6	.7	.8	.9	1.0	1.1	1.2	1.4	1.5	1.6	1.7	1.8	1.9	2.0	
	9	.6	.7	.8	1.0	1.1	1.2	1.3	1.5	1.6	1.7	1.8	2.0	2.1		
	10	.6	.7	.9	1.1	1.2	1.3	1.4	.6	1.7	1.8	2.0	2.2			
	11	.6	.8	.9	1.1	1.2	1.4	1.5	1.7	1.8	2.0	2.3				
	12	.7	.8	1.0	1.2	1.3	1.5	1.6	1.8	2.0	2.3					
	13	.7	.8	1.0	1.3	1.4	1.6	1.7	1.9	2.1						
	14	.7	.9	1.1	1.3	1.5	1.7	1.8	2.0							
	15	.7	.9	1.1	1.4	1.6	1.8	2.0								

TIME IN HOURS

and assembled accurately. Table 4 provides the time estimates for squaring many sizes of oil-hardening tool steel block in the unhardened state. For blocks of soft steel, 70 per cent of the specified values are sufficient. For high-carbon high-chrome steel and other tough materials, values 120 per cent of those in the table should be used.

NOTE: The authors state that there is a fixed relationship between the time for squaring a given block and the time necessary for grinding it and accordingly specify that the following basis for ascertaining the grinding time be used.

For plain setup–50 per cent of above values plus 0.1 hour.

For indicator setup–50 per cent, plus 0.3 hour both before and after heat treating, which is thus the equivalent of 100 per cent of the table value for squaring plus 0.6 hour.

NOTE: If a piece of cold-rolled steel, or other material which requires no heat treatment, is to be ground, 50 per cent of the squaring-up time is used plus 0.1 hour for setting up in the surface grinding.

If the piece to be ground is tool steel, it will generally have to undergo the grinding operation preparatory to layout and then another after it has been heat treated. Therefore, 100 per cent of the squaring up time is added, plus 0.2 hour for setting up. If the setup is intricate, however, and requires the use of the indicator, 0.6 hour is added to the grinding and squaring time.

Every figure given has been established and actually used. All the figures include allowances for all reasonable contingencies such as waiting for a machine and time to study the print. Additional tables have been prepared to include the grinding time in accordance with the rules for its calculation, as given above.

EXAMPLE 15: The die block shown in Fig. 89 is $1\frac{1}{8}$ in. × 3 in. × 4 in. The nearest thickness according to Table 4 is 1 in. The corresponding time value in conjunction with a 3-in. width and 4-in. length is 0.6 hour.

For the grinding time involving two setups:

$$2 \times 0.50 \times 0.6 + 2 \times 0.1 = 0.8 \text{ hour.}$$

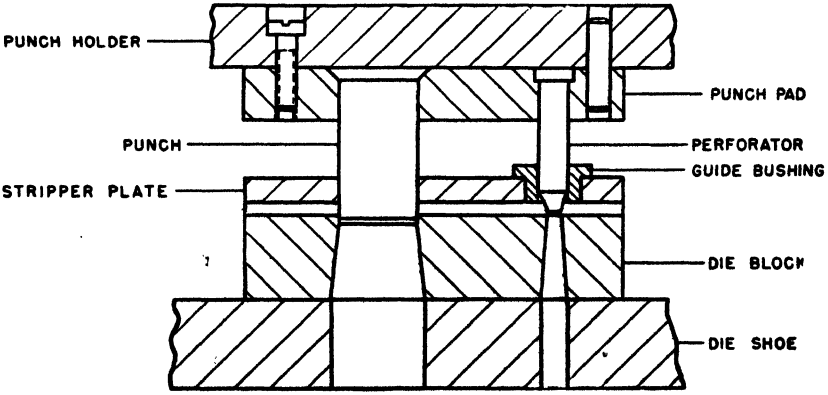


Fig. 89. Cross section of die, showing details.

Thus, squaring and grinding of the die block will require 1.4 hours. Of course, other work will have to be done to complete the die block, as indicated for groups B, C, and D, and its extent is determined from other tables of similar type.

The punch to be used in the same die requires a block 1 in. × 1 in. × 2 in. From Table 4 its machining time is 0.3 hour. Its grinding time will need be

$$0.3 \text{ (table value)} + 0.2 = 0.5 \text{ hour}$$

and total time will be 0.8 hour.

The punch pad has dimensions $\frac{5}{8}$ in. × 3 in. × 4 in. (Nearest table value $\frac{1}{2}$ in. × 3 in. × 4 in.) and a time of 0.5 hour. Since the pad is made of cold-rolled steel, only 70 per cent of the table value, or 0.35 hour is required. Here, 0.4 hour is used for an approximation. Only one grinding setup is required and thus:

$$0.4 \times 0.5 + 0.1 = 0.3 \text{ hour}$$

and the total time for the squaring of the pad will be 0.7 hour.

The stripper plate is $\frac{1}{2}$ in. × 3 in. × 4 in. and its squaring time is likewise approximately 0.4 hour and grinding time 0.3 hour for a total of 0.7 hour.

Small punches or perforators are common components of dies and of more or less standard design. In some shops they are turned out or bought in quantities and stocked until needed. The means of estimating their cost is another example of the method under discussion. Figure 90 illustrates four commonly used types. Numbers 1 and 2 are applicable to production runs not exceeding 50,000 pieces with stock not over $\frac{1}{16}$ in. in thickness. For heavier materials and longer runs, type 2 is preferred. Type 3 is more expensive, but performs more accurate work. Type 4 is intended for small holes and the perforator is fitted inside the bushing or quill for support. The letters P, G, or L alongside the outlines stand for the finish

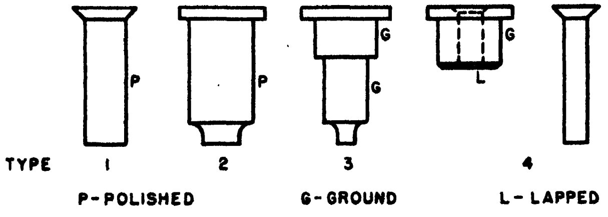


Fig. 90. Types of perforators in common use. (From Bohmer and Dannes, *Die Designing and Estimating*, Huebner Publications, 1942, by permission of the publisher.)

desired: Polish, Grind, or Lap. Table 5 presents average time value for making various sizes of the perforators shown in Fig. 90. Of additional interest is the circumstance that die bushings and guide bushings have been found to require about the same time as does a type-3 perforator of equivalent size.

TABLE 5

TIME VALUES FOR MAKING AND FINISHING PERFORATORS, PILOTS, AND DIE BUTTONS

Type	Time in hours		
	1	2 each	5 or more each
1 up to $\frac{5}{8}$ in. dia.	0.7	0.5	0.4
2 up to $\frac{5}{8}$ in. dia.	0.9	0.7	0.6
2 over $\frac{5}{8}$ in. dia.	1.2	0.9	0.7
3 up to $\frac{5}{8}$ in. dia.	2.0	1.5	1.0
3 over $\frac{5}{8}$ in. dia.	2.5	2.0	1.4
4 of $\frac{1}{8}$ in. dia.	3.0	2.5	2.0
4 of $\frac{1}{16}$ in. dia.	4.0	3.0	2.5
4 of $\frac{1}{32}$ in. dia.	5.0	4.0	3.0

EXAMPLE 16: The perforator of the die of Fig. 89 is $\frac{3}{8}$ in. in diameter. From Table 5, the time required for making it is 0.9 hour. A guide bushing $\frac{5}{8}$ in. in diameter is also needed in the stripper plate to support the perforator. Its time value, the same as for a type-3 perforator of $\frac{5}{8}$ in. in diameter is 2.0 hours. The total time required for making the perforator and guide bushing is therefore 2.9 hours.

ESTIMATING PREPARATION PERIOD

Of vital concern to a tooling program is an estimate of the date on which the tools and equipment will be available and production activity can begin. Material and production schedules are dependent on that expectation. The tool engineer is usually required to ascertain the length of time needed for preparation of the tooling, along with an estimate of cost. Obviously, the actual fabrication time alone is seldom the elapsed time for a tooling program

Toolroom organization

The organization of a toolroom determines to some extent the necessary preparation period for tools. There are two basic forms of toolroom organization. In one, each toolmaker is assigned specific jobs and carries them through from start to finish; machining the details and then fitting and assembling them. He may work on several jobs concurrently, setting one aside when a machine is not available and taking up another. Under such a system the elapsed time approaches the actual working time but is usually somewhat longer because of unavoidable delays and interferences.

In the second type of organization, the toolmakers let out the machining of the details to specialists operating the machine tools in the toolroom. The toolmakers also work in groups, headed by a group leader of better than average ability and skill. He allots the preliminary fitting and assembling to less skilled men in the group and takes care of only the most exacting jobs himself. The system of specialization and utilization of all degrees of skill offers the most economical means of toolmaking but does tend to lengthen the period of elapsed time for all jobs. A substantial backlog of work is desirable for smooth functioning and the likelihood of interferences and delays is increased.

Factors affecting delivery

In any plant, situations are always arising which demand that some tools be made immediately. Breakdowns and unforeseen production difficulties are not uncommon in the best regulated factories and necessitate repairs and additions without delay. The highly departmentalized toolroom is not suited to rush jobs. Sometimes for emergencies a smaller toolroom of the first type is operated along with the regular toolroom of the second type. A tracer system may be employed in a systematized toolroom to expedite urgent jobs, although this tends to disrupt the routine and increase costs. In any event, under constant pressure, the elapsed time for a job can usually be reduced to an amount close to the actual working time.

For routine jobs which do not warrant special attention, the backlog of orders having precedence in the toolroom is the first factor determining elapsed time. A toolmaker is usually not given more than a few jobs at a time. Too many tasks at once merely serve to clutter his work place and most of the assignments cannot be given attention anyway until he gets around to them. Customarily there is a certain float in the toolroom, and excess projects are set aside and assigned as completed jobs are returned. By watching this

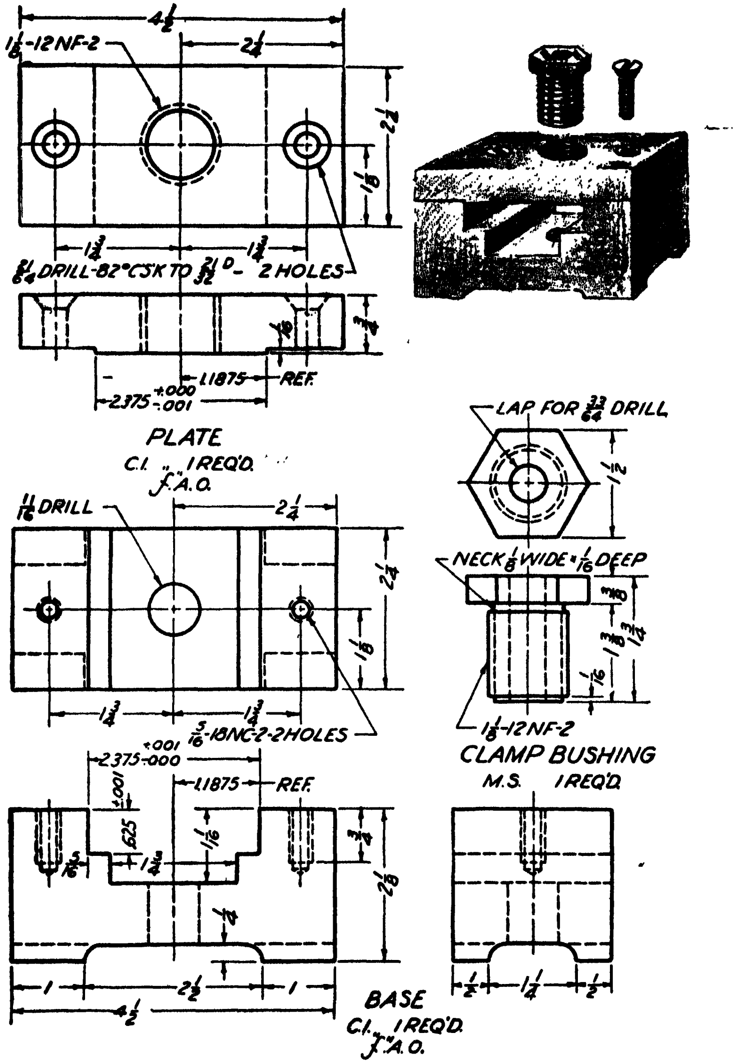


Fig. 91. The details of a drill jig. (From Luzadder, *Fundamentals of Engineering Drawing*, p. 352, Prentice-Hall, 1946.)

situation, the tool engineer can surmise when a job is likely to be started. From there, a reasonable supposition is that the time until completion will be about the same as for previous similar jobs. A record of dates on which each job is started and completed should be kept for the toolroom. These data will prove the most reliable basis for estimating future performance.

SUMMARY

Detailed analyses are not always necessary for cost estimating. Short cuts may serve as well. These may be in the form of approximate factors relating the machining time to the over-all time of production, fabrication and assembly to designing and detailing, or machining to fitting and assembling. General formulas for specific functions have also been used. Care and discretion must be exercised in applying approximations.

A variation of tool estimating that has been applied successfully treats the cost factors in groups. Consideration of individual operations is not necessary. Proven results for the various groups may be tabulated for easy reference.

The period of time that must elapse before a tool will be ready is also a subject requiring estimating. That time depends upon the toolroom organization, the backlog of work in the toolroom, the amount of follow-up, and the performance shown on previous jobs.

Problem 37. Estimate the total time to fabricate the drill jig of Fig. 91. Consult manufacturers' catalogues for prices of standard items. Use one or more of the following methods:

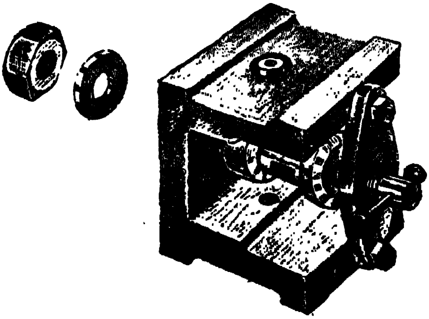


Fig. 92A. Tumble jig. (Figs. 92A and B are from Luzadder, *Fundamentals of Engineering Drawing*, pp. 366, 367, Prentice-Hall, 1946.)

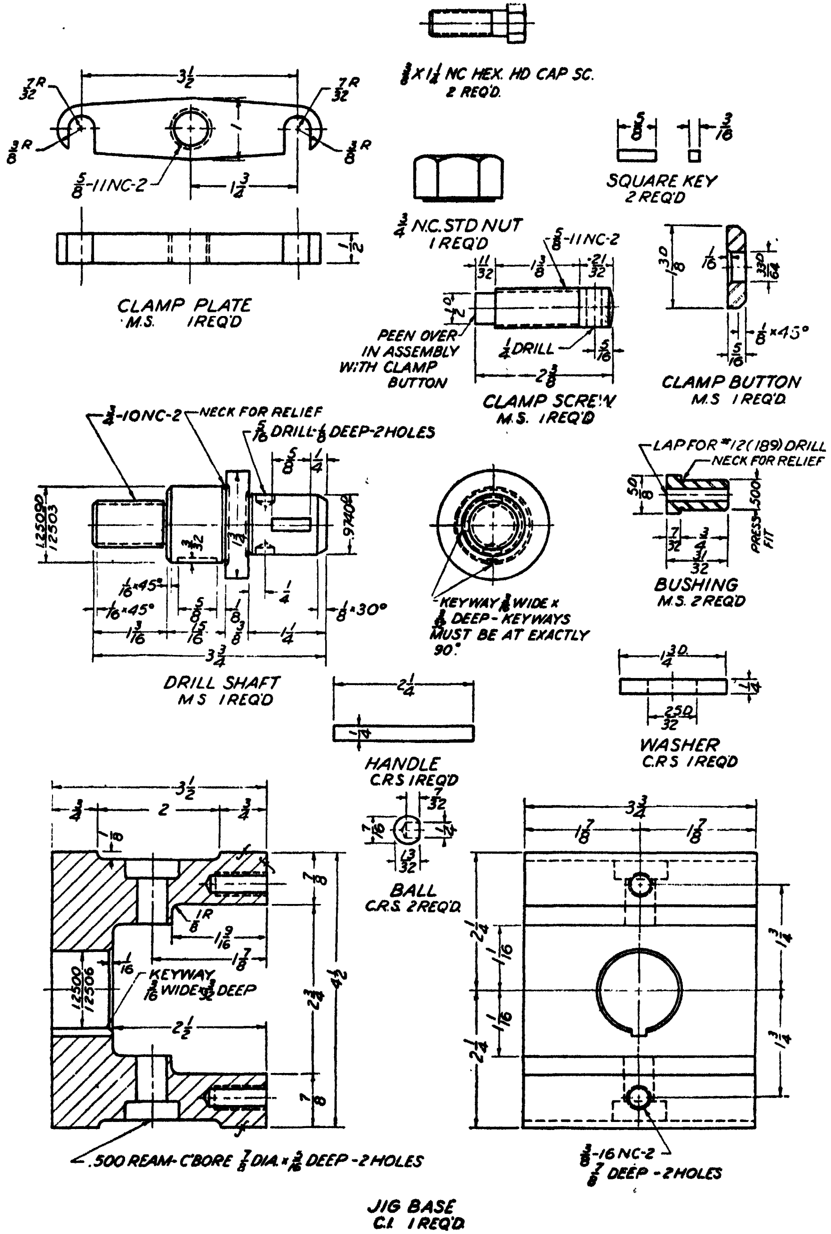


Fig. 92B. The details of a tumble jig.

(a) List the operations for each detail. Calculate machining time for each operation. List elements and get values for them from tables in a handbook, reference book, or plant. Add suitable allowances.

(b) Calculate machining time for each detail and multiply it by a suitable factor for over-all time. Increase over-all time by enough to take care of fitting and assembly.

(c) Break down the work to make the jig into groups of related cost factors, like Group A—machining; Group B—holes; Group C—layout, etc. From tables in references, handbooks, or plant records, obtain reasonable time values for the groups:

Problem 38. Estimate the total time to fabricate the drill jig of Fig. 92. Use one or more of the methods outlined for Problem 37. The drill bushings and drill shaft of Fig. 92 are to be carburized and hardened except on the threads. Consult manufacturers' catalogues for prices of standard items.

Problem 39. Estimate the total time to fabricate the drill jig of Fig. 93. Use suggestions in Problems 37 and 38.

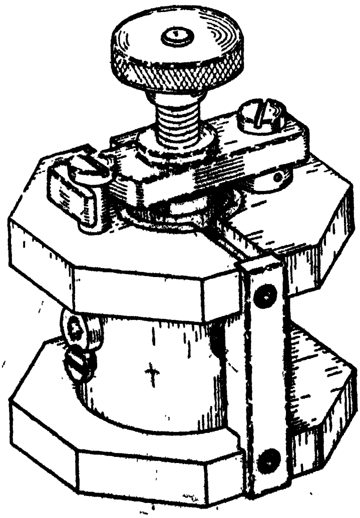


Fig. 93A. Drill jig. (Figs. 93A and B are from Luzadder, *Funda-*

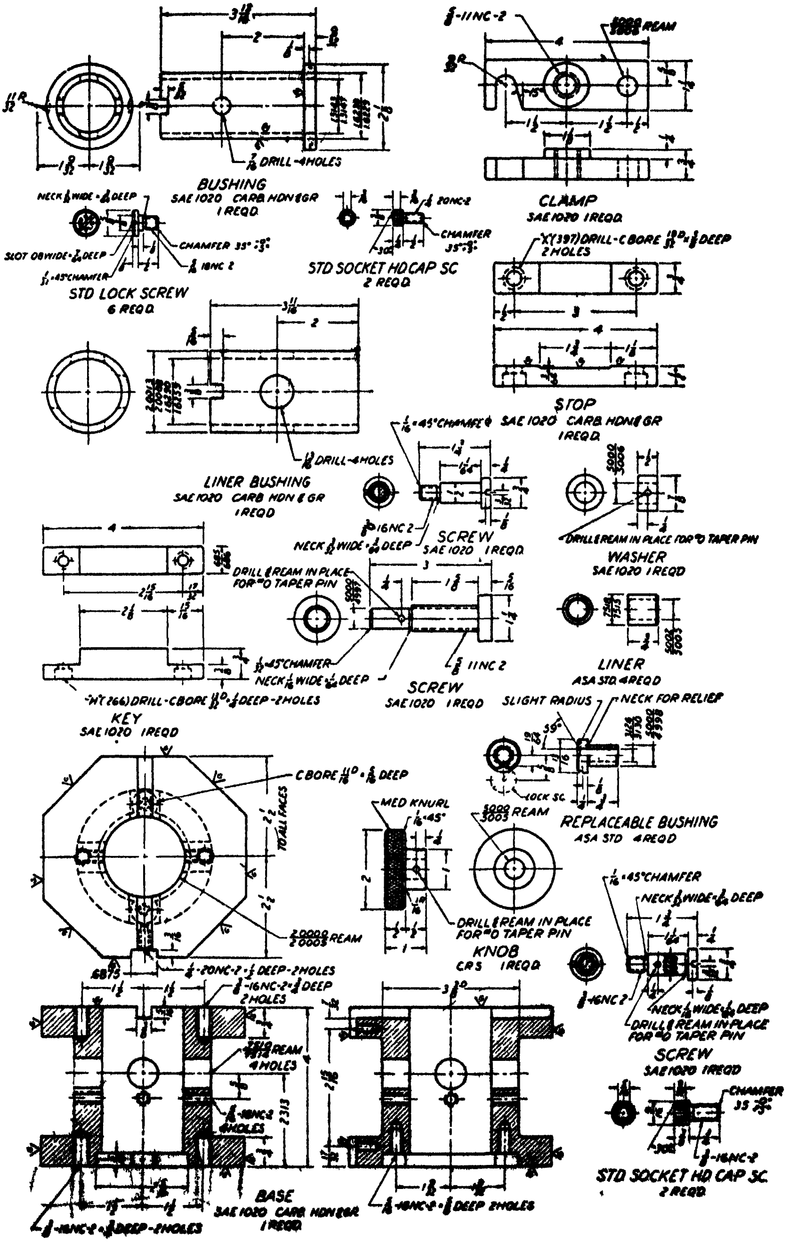
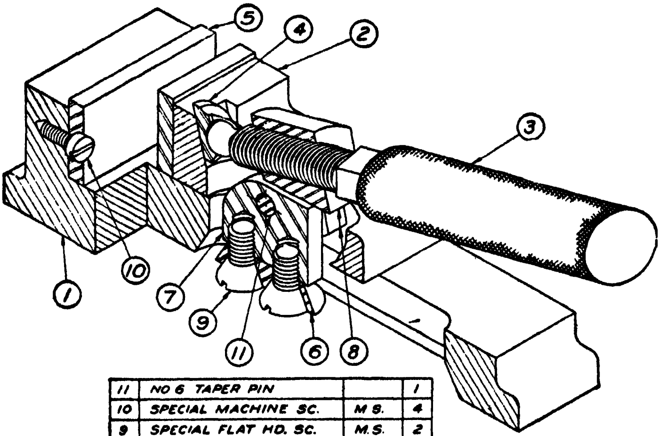


Fig. 93B. The details of a drill jig.

Problem 40. Estimate the total time to fabricate the hand-clamp vise of Fig. 94. Follow suggestions in Problems 37 and 38.



PART NO.	NAME OF PART	MATERIAL	NO. REQ.
11	NO 6 TAPER PIN		1
10	SPECIAL MACHINE SC.	M S.	4
9	SPECIAL FLAT HD. SC.	M.S.	2
8	LINK	C.R.S.	1
7	COUPLING	C.R.S.	1
6	WEDGE	C.R.S	1
5	JAW PLATE	C.R.S.	2
4	SHOE	C.R.S.	1
3	HAND SCREW	C.R.S.	1
2	JAW	C.I	1
1	BASE	C.I.	1

Fig. 94A. Hand clamp vise.

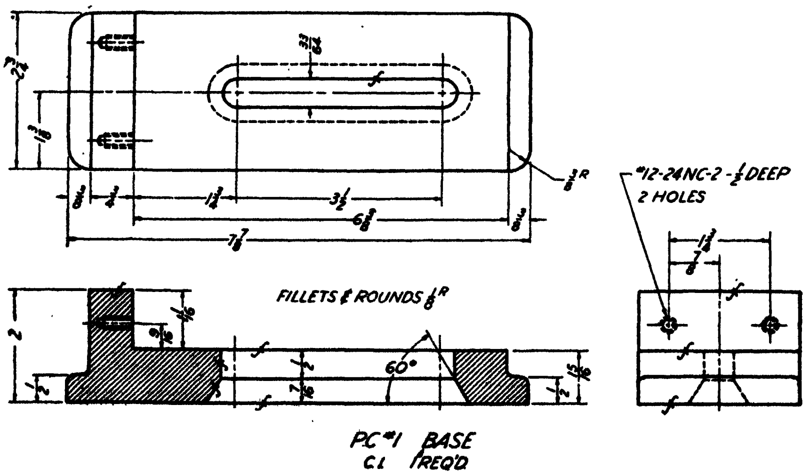


Fig. 94B. Details of a hand clamp vise.

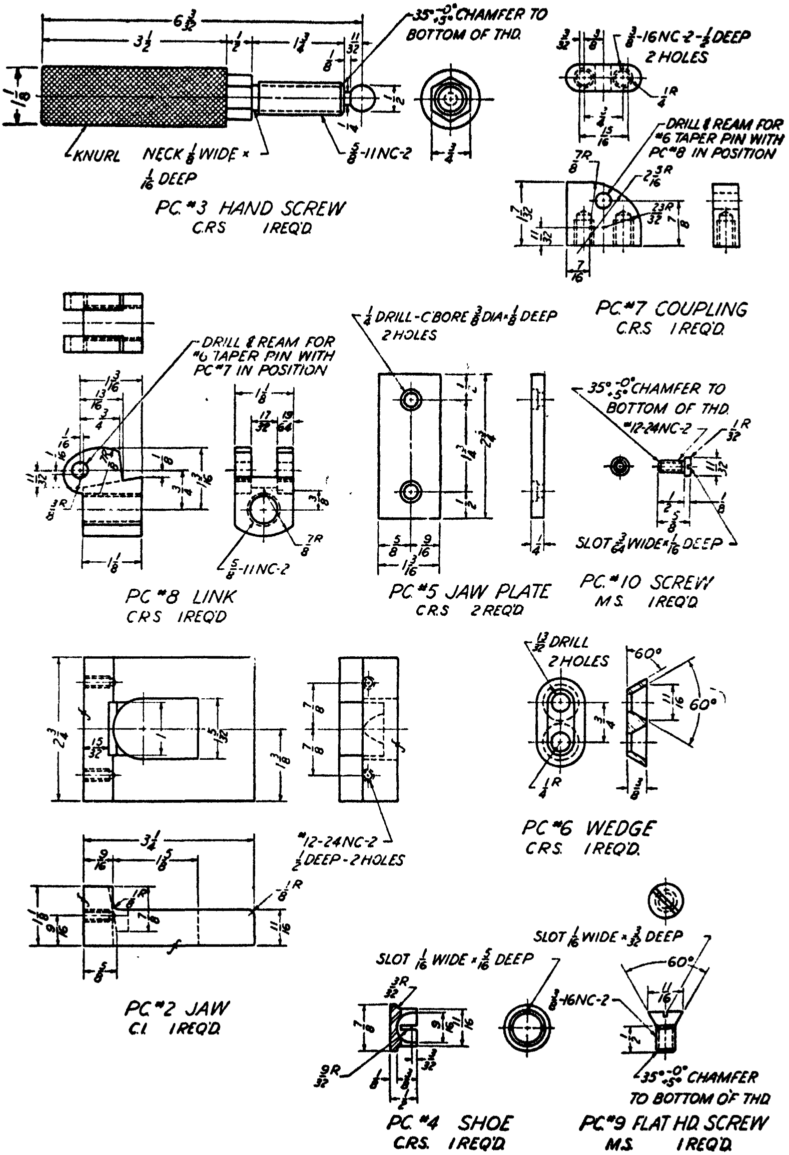

PC #3 HAND SCREW
CRS 1 REQ'D
KNURL
NECK 1/8 WIDE × 1/16 DEEP
5/8-11NC-2
35°+0°-5° CHAMFER TO BOTTOM OF THD.
3/8-16NC-2-1/2 DEEP 2 HOLES
DRILL & REAM FOR #6 TAPER PIN WITH PC #8 IN POSITION
PC #7 COUPLING
CRS 1 REQ'D
DRILL & REAM FOR #6 TAPER PIN WITH PC #7 IN POSITION
PC #8 LINK
CRS 1 REQ'D
1/4 DRILL-C'BORE 3/8 DIA × 1/8 DEEP 2 HOLES
PC #5 JAW PLATE
CRS 2 REQ'D
#12-24NC-2
SLOT 3/64 WIDE × 1/16 DEEP
PC #10 SCREW
MS 1 REQ'D
13/32 DRILL 2 HOLES
PC #6 WEDGE
CRS 1 REQ'D
#12-24NC-2 1/2 DEEP-2 HOLES
PC #2 JAW
CI 1 REQ'D
SLOT 1/16 WIDE × 5/16 DEEP
SLOT 1/16 WIDE × 3/32 DEEP
3/8-16NC-2
35°+0°-5° CHAMFER TO BOTTOM OF THD.
PC #4 SHOE
CRS 1 REQ'D
PC #9 FLAT HD SCREW
MS 1 REQ'D

Fig. 94C. Details of a hand clamp vise. (From Luzadder, *Fundamentals of Engineering Drawing*, pp. 362, 363.)

QUESTIONS

1. Under what circumstances are detailed estimates desirable, and when are short cuts in order?

2. What kinds of factors may be used for quick estimates?

3. What kinds of approximate formulas may be used to estimate specific functions?

4. What features of tools make it possible more or less to standardize methods of estimating their cost?

5. Classify the steps required to make the drill jig of Fig. 91 into groups according to the similarity of the functions performed.

6. Classify the steps required to make the drill jig of Fig. 92 into groups according to the similarity of the functions performed.

7. Classify the steps required to make the drill jig of Fig. 93 into groups according to the similarity of the functions performed

8. What advantages are gained by classifying the work to make a tool into groups of similar functions?

9. Why is it necessary to estimate the preparation period of a tool?

10. Describe two forms of toolroom organization.

11. What factors affect the length of time that is likely to elapse before a tool will be ready for use?

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7 MANUFACTURING PRINCIPLES APPLICABLE TO PROCESS AND TOOL PLANNING

The significance of planning

Manufacturing proceeds from a number of stages and forms of planning. First, and most comprehensive, is administrative planning, which sets in motion, co-ordinates, and controls the enterprise as a whole and creates the policies to guide those under the direction of the management. Concerned with the solution of the physical problems of production, the technicalities of how to carry out the policies and decisions of management, is production engineering, which includes the activities of process and tool planning, time and motion study, and plant layout. Issuing from these is temporal planning, done under the names of scheduling and dispatching, which co-ordinate materials, men, and machines to conform to the technical plans. Scheduling determines the rate at which they shall function. Dispatching starts and maintains the action.

The highest productive efficiency is found when the required quantity, of the required quality, at the required time, by the best and cheapest method is produced. This is the goal of industrial management. It is secured by providing the required amount of material, proper machines and tools, the necessary personnel, and adequate instructions at the right time and place. To reach, or even approach, this ideal, planning is necessary. Henry L. Gantt stated that well-thought-out plans, together with complete instructions, can produce over 100 per cent more than is commonly done otherwise, if the limiting factor is physical exertion. Furthermore, the ratio of what can be done to what is often done may be even greater than three to one in work requiring skill and planning.

The manufacture of an article involves a process or method; a series of actions or operations leading to a definite accomplishment. Usually several processes, or at least a number of variations, are available for doing a job. So that those who prepare for the process and those who carry it through can direct their efforts towards the most desirable method, a master plan is necessary. The formation of a good plan requires that the process be well-understood and described in a concise and usable form.

Time and again the necessity of planning as a basis for tooling has been proven. A large project is started, and the drawings of the parts to be made are distributed among a number of tool designers or tool makers. Without planning there is no co-ordination between them. One person is concerned with several operations, another person with other operations, etc. Each has his own ideas as to how the work should be done, and creates the tools for his operations accordingly. The supervisors must carry in their heads a mass of details and cannot hope to keep it all straight. When production is attempted, pieces from early operations are found unsuitable for later ones. Some machines are overloaded; others almost idle. Tolerances pile up and dimensions come consistently out of limits and out of control. As a result of these faults and many others, production is snarled. A flow of good parts is only obtained after many revisions and alterations have been made. This is not an imaginary situation but is typical of what has occurred many times in large plants where tooling programs have been attempted without adequate preparation.

A good tooling program is important to the success of a process. It can be fully effective only if it is guided by a sound plan. Planning recognizes ahead of time the problems likely to be met and thus provides the following benefits:

1. The elimination of waste and inefficiency caused by confusion in the design of tools, fixtures, jigs, dies, and gages.
2. The elimination of expensive cut-and-try methods and expensive redesign and alteration of tools.

The course of efficient manufacturing is charted by basic principles or rules which define the conditions for successful performance. Many of these apply to phases of manufacturing with which the process or tool engineer is not directly concerned. Several, however, are fundamental to process and tool planning. They prescribe, directly or by implication, what it must accomplish and observe. These principles pertain to:

1. The necessity for an expression of objectives.
2. The division or specialization of effort.
3. The advantages of interchangeable manufacture.
4. The utilization of machines and tools.
5. The handling of material.
6. The control of quality.
7. The economical justification of machines and tools.

Expression of objectives

A necessary preliminary to an industrial project is a clear, complete statement of its object with which each activity can be harmonized. Consequently, a process must be definitely identified. Its plan must stipulate the product for which it is intended, the quantity of pieces it is expected to produce, its relationship to the over-all scheme, and the time for which it is authorized.

Division or specialization of effort

Division of labor is a cardinal principle of modern manufacturing. Workers who specialize and concentrate on one or a few tasks acquire a proficiency from practice that increases the quantity and quality of their output. Efforts of adaptation and continuance are reduced. Under this precept, each worker is assigned one or a very few manual or mental tasks which he is capable of performing and can learn quickly.

Division of effort permits the application of just the right amount of skill and force to each operation. If one workman or one machine were required to complete an entire process, he or it would have to possess the maximum amount of skill and strength required by any part of it. On the other hand, if the process is divided, only that amount of skill or strength applicable to each subdivision needs to be applied. As a result the construction and use of machines devoted to specialized tasks are feasible.

To promote specialization and simplification, the mental labor of production should be reduced to a minimum by planning beforehand what work shall be done and how, when, and where. To designate division of labor, processes are divided into operations. A process plan should, therefore, define the extent and nature of specialization expected by a complete list of the operations showing their sequence in the process and placement within the plant.

Through division of labor and specialization the labor base can be broadened. Unskilled and semi-skilled laborers, even those possessing a minimum of intelligence, can be employed. Such workers, however, cannot be expected nor depended upon to comprehend the intricacies of properly routing work through a shop nor even, in many cases, to direct their own efforts. With less capable subordinates, supervisors have more of their time consumed by a multitude of details and less of it available for contemplation of the broader aspects. In fact, with less skilled workers, the preference is for supervisors with personnel rather than technical inclinations, and consequently, the need for technical service is greater. As the tendency towards specialization is intensified, the necessity of planning the form and sequence of operations beforehand and of issuing complete instructions is augmented. Thus, in its more extended form a process plan may specify the results expected from each operation and present directions for obtaining them efficiently.

Interchangeable manufacture

Interchangeable manufacture is fundamental to quantity production of mechanical devices. It is based upon the idea of making each dimension of all the pieces of a part of a machine or assembly enough alike so that any of the pieces will fit and function properly in any of the assemblies. It is helpful in the following ways:

1. For some products it provides ease of assembly for the manufacturer.
2. It may make repairs easier and thus benefit the user of the product. This second advantage may be nullified to some extent by the first. For instance, it often is not economical to repair cheap watches, even though replacement parts are obtainable, because of the low cost of the watches made possible by interchangeable manufacture.
3. Interchangeable manufacture may provide the means for the utility of the product, as is the case with fixed size wrenches or electric light bulb sockets which must conform closely to standards.
4. Interchangeable manufacture reduces cost by standardizing methods of manufacture. Within a process interchangeable parts can be held and located within definite limits and can be worked in a predictable manner.
5. Interchangeability has made dispersion of facilities possible

as manufacturing has grown. It is not uncommon for the same parts of a mechanism to be made simultaneously in two or more factories. If one source fails, there is not a complete cut-off of supply. The parts made in all plants can be depended upon to correspond, particularly if the same methods are employed by all suppliers.

Interchangeability is realized by permitting a variation or tolerance from the basic size of each dimension. That may be large or small, depending on the requirements, but maintenance of tolerances depends upon operational control. In production machining, an attempt is made to bring all workpieces coming to an operation into the same relationship with the tools. That is why fixtures and jigs are used to locate workpieces uniformly. But every means to that end adds some error, no matter how small. Thus errors are introduced by variations in location of the workpiece, by the action of the cutting tools, by inaccuracies in the machine, and by the human element. The possible effect of each factor must be appraised, and the sum of all recognized, if required results are to be assured. Then to make certain that the errors do not exceed expectations, the nature of each arrangement must be clearly stated. In other words, a process plan should take into account the locating of the workpiece, specifying the locating surfaces on the part and the device for making contact with these surfaces. It should include a description of the tools and machines and call for such equipment as will perform within the desired limits. And last, but not least, it should not overlook the human factor and should provide necessary means to aid the operator in doing the job right.

Principles pertaining to the utilization of tools

Tools and machines are utilized to derive advantages as expressed in the principles of:

1. Mechanical advantage, as found in clamps and levers.
2. Advantage of perception, as illustrated by the dial and lead-screw on a machine tool whereby minute increments of movement or distance are magnified so as to be readily visible to the operator.
3. Transfer of power, whereby means are provided in a machine for applying power from an external source to supplement and even replace human exertion.
4. Transfer of skill and thought to machines and tools that duplicate the craftsman's performance and need relatively inexpert atten-

tion. The common drill jig is an example. An automatic machine which repeats each step of a cycle without continuous attention is another case.

5. Simulation of action, whereby several elements of an operation are performed simultaneously. A machine tool arranged to take several cuts at once carries out one aspect of this principle. Another is found in an operation arranged so that the operator can load one fixture, while the machine is working on a piece in another fixture.

Obviously, a process and tool plan must give attention to the characteristics of the machines and tools needed to take advantage of these principles. For instance, the clamping means to be provided on fixtures should be understood if assurance is to be given that adequate mechanical advantage will be derived without distortion. If dimensional limits are close, gages should be specified which will offer the operator the means of perceiving results accurately. The size, type, and make of each machine tool should be determined to assure sufficient capacity and available power. Where transfer of skill and thought is intended, a clear idea of how it is to be accomplished is necessary.

Material handling

The moving and handling of materials is often a sizeable part of a process. Economy in handling materials is promoted by reducing the number of operations (decreasing the number of times each piece is handled), by moving material in a straight line, by decreasing the distance over which materials must be transported, and by providing efficient carriers. Detailed consideration of material handling methods is usually not within the province of process planning, but the relationship of the two must not be overlooked. Any process and tool plan must take cognizance of such factors as the locations of machines and the design of fixtures, etc., that facilitate handling.

Control of quality

Quality control is essential to quantity production. It adds to the productive effort, but increases the output of salable goods and improves the competitive position of the product. Inspection is the usual means for the control of quality. It may be preventive, taking place at the machines. It may occur at strategic stations throughout the process, or it may take place upon completion of the parts.

A decision needs to be made as to the proper place of inspection in a process, and the process plan should reflect that decision.

But inspection alone is a passive means of enforcing accuracy. Quality, if it is to be real, must be manufactured into a product. The causes of errors and the means of controlling them must be known. This presents a challenge for good planning and tooling that will make it easy for the man at the machine to produce the required quality with no more effort than not to do so.

The economic justification of machines and tools

As has been pointed out, mechanization provides definite processing advantages. However, the extent to which its use is warranted in any case is a matter of economics. That has been discussed in Chaps. 2, 3, and 4, dealing with economic principles. Dexter S. Kimball has summarized this idea as the basic principle of mass production: the larger the number of units that are to be made of a product, the greater the time and money that can economically be expended upon preparation and planning. Since a process and tool plan implies a certain investment to carry it out, it follows that in its conception adequate investigation must be made of the justification for its requirements.

Contents of a process and tool plan

On the basis of the principle discussed, the contents of a process and tool plan can be summarized as follows:

1. An identification of the process and an indication of its purpose, comprising the definite information of:

   a. The name and identification number or symbol of the article for which the process is intended.

   b. The quantity to be produced by the process and/or the number of parts in each lot.

   c. The description of the material from which the part is to be made; its rough condition, shape, weight, or size.

   d. The model or assembly for which the specific part is intended (or if an assembly, an identification of its components) and the number of parts in each assembly.

e. The date on which the project becomes effective. When the limit of usefulness is known, a superseded date may also be in order.

f. An identification of the person compiling the plan.

g. Filing numbers or code for the paper work.

h. The number of the order providing authority for the activity.

2. A conception of the division of labor to be undertaken in the process, including:

a. A list of the operations specifying the steps to be taken during the process.

b. A numbering system designating the position of each operation in the process and the sequence of the operations.

c. A designation of the department in which each operation is to be conducted and the location within the department.

3. A description for each operation of the manner in which it conforms to the principles of interchangeable manufacture and control of quality. This may include the following points:

a. The locating surfaces on the workpiece and the clamping areas.

b. Specifications of the requirements of the operation:
  The dimensions and tolerances to be maintained.
  The geometrical relationships of the affected surfaces.
  The surface finish required.
  The physical condition to be imparted to the material.

c. The placement of the inspection function within the process.

4. A description of the equipment and how it is to be used specifying:

a. The size, type, and kind of machine.

b. Necessary machine attachments and accessories.

c. The location of equipment if already on hand.

d. Instructions for setup of the equipment, the speeds and feeds to be used, the number of parts to be worked on at one time, etc.

e. Standard and special cutting tools, holding devices, jigs, fixtures, dies, and gages, designating:
  The quantity of each item of equipment required.
  The clamping means.
  The locating devices.

Identification numbers of special tools; file numbers for storage of tools.

5. The performance requirements of each operation, in the form of:

    a. The estimated or standard time to operate on each piece.

    b. The amount of production expected in a certain length of time.

    c. The capacity of the equipment.

SUMMARY

Process and tool planning is an important step in carrying out the policies and plans of management. If tooling is to be economical and effective, it must be based upon good planning, done in accordance with recognized principles of manufacturing. These principles have to do with:

1. The necessity of expressing objectives.
2. The division and specialization of labor.
3. Interchangeable manufacture.
4. The use of machines and tools.
5. The handling of material.
6. The control of quality.
7. The economics of machines and tools.

A process and tool plan should be built on these principles and account for them in its framework by:

1. Identifying its purpose.
2. Specifying the extent to which effort is divided.
3. Designating the methods, machines, and tools to be used, how they fit into the general plant layout, and their features to insure quality.
4. Stating the results expected of the process.

Conventional ways of doing this and an outline of planning procedure are contained in the next chapter.

QUESTIONS

1. Describe four stages of industrial planning.

2. What benefits may be derived from good industrial planning?

3. What is necessary for a successful tooling program? Why?

4. Specify the principles of manufacturing relevant to planning.

5. Why must a process be definitely identified in the plan made for it? How is that done?

6. What are the advantages of division of labor?

7. How does a process plan specify the specialization and division of labor expected?

8. What is meant by interchangeable manufacture?

9. What are the benefits of interchangeable manufacture?

10. What provisions of a process and tool plan are necessary to insure interchangeability?

11. How are advantages derived from tools?

12. What attention must be given in a process and tool plan to the features of machines and tools?

13. How is economy of material handling promoted?

14. In what ways can a process and tool plan contribute to economical material handling?

15. What benefits offset the cost of quality control?

16. In what two ways may accurate results be secured in production?

17. What precautions must be taken in planning to assure justification of the investment in tools and equipmen ?

18. What general information should a process and tool plan have to assure conformance to the principles of manufacturing?

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8 PLANNING PRACTICES

WAYS OF EXPRESSING PROCESS AND TOOL PLANS

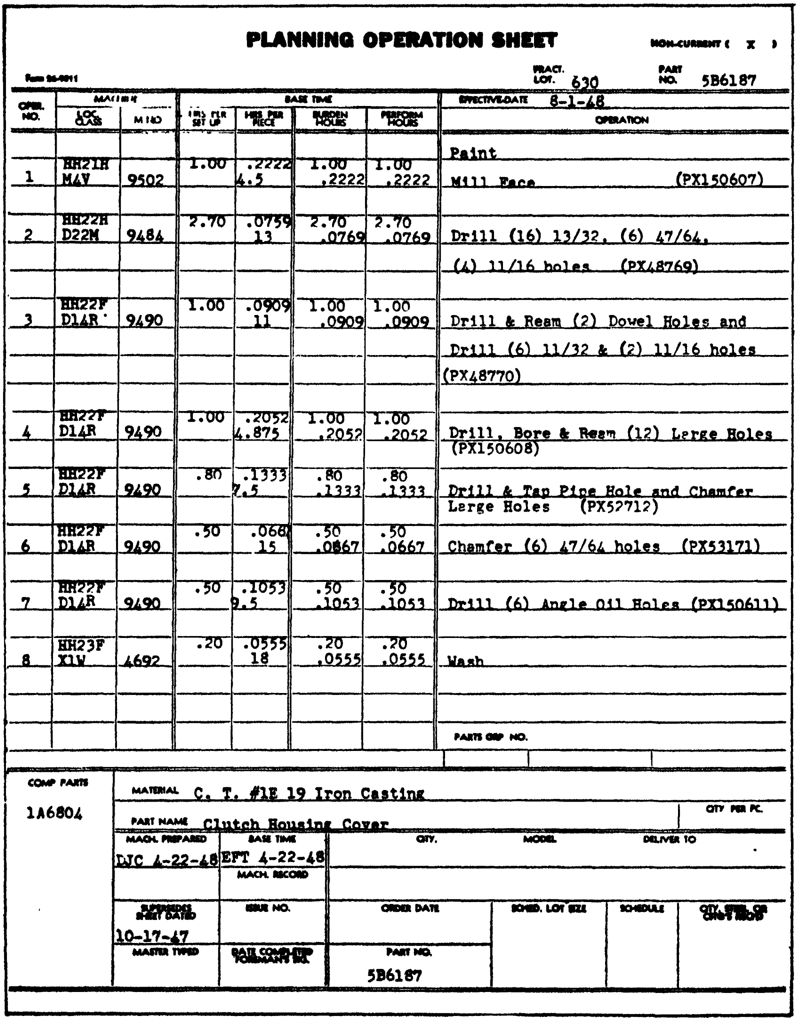
Conditions affecting extent to which plans are manifested

There are numerous practical ways of transmitting and recording process and tool plans. In primitive organizations, the plans may be carried in the minds of the shop supervisors and their assistants with instructions to carry out these plans given orally as needed. In many organizations, precedent and convention dictate a large measure of process procedure, and planning records are supplementary and sketchy. If the workmen in a plant are highly skilled and capable, detailed instructions may be superfluous and many of the process ramifications may be entrusted to their judgment. On the other hand, directions may have to be detailed and explicit where innate ability is lacking. A continuous long range project does not need as complete records as does one discontinued and then repeated at intervals and likely to be forgotten. These and similar circumstances determine the extent to which process plans are actually expressed on paper in various plants.

In application, the actual mode of expression varies all the way from the purely oral to highly refined systems of recording data. The fact that in some plants certain parts of the process plans are not recorded does not mean that plans do not exist. They must be present in some form or other, perfected or defective, wherever manufacturing is carried on in accordance with established principles. Under whatever circumstances, it is essential that the engineer be able to perceive the tenor of planning and utilize it for effective preparation for production.

Routing and tool order forms

A major record of process and tool planning is the routing, also known as route sheet, process sheet, planning operation sheet, or by some similar name. Its purpose, in brief, is to describe what is to be done in the process. These sheets are found in many forms. Figure 95 shows one type of route sheet. In its heading and subtitle it identifies the part and in its body contains a list of the opera-



PLANNING OPERATION SHEET

NON-CURRENT (X)

Form 26-0011

TRACT. LOT. 630

PART NO. 5B6187

OPER. NO.	MACHINE		BASE TIME				EFFECTIVE-DATE 8-1-48
	LOC. CLASS	M NO	HRS PER SET UP	HRS PER PIECE	BURDEN HOURS	PERFORM HOURS	OPERATION
							Paint
1	HH21H M4V	9502	1.00	.2222 4.5	1.00 .2222	1.00 .2222	Mill Face (PX150607)
2	HH22H D22M	9484	2.70	.0759 13	2.70 .0769	2.70 .0769	Drill (16) 13/32, (6) 47/64, (4) 11/16 holes (PX48769)
3	HH22F D14R	9490	1.00	.0909 11	1.00 .0909	1.00 .0909	Drill & Ream (2) Dowel Holes and Drill (6) 11/32 & (2) 11/16 holes (PX48770)
4	HH22F D14R	9490	1.00	.2052 4.875	1.00 .2052	1.00 .2052	Drill, Bore & Ream (12) Large Holes (PX150608)
5	HH22F D14R	9490	.80	.1333 7.5	.80 .1333	.80 .1333	Drill & Tap Pipe Hole and Chamfer Large Holes (PX52712)
6	HH22F D14R	9490	.50	.0667 15	.50 .0667	.50 .0667	Chamfer (6) 47/64 holes (PX53171)
7	HH22F D14R	9490	.50	.1053 9.5	.50 .1053	.50 .1053	Drill (6) Angle Oil Holes (PX150611)
8	HH23F X1W	4692	.20	.0555 18	.20 .0555	.20 .0555	Wash

PARTS GRP NO.

COMP PARTS 1A6804

MATERIAL C. T. #1E 19 Iron Casting

PART NAME Clutch Housing Cover

QTY PER PC.

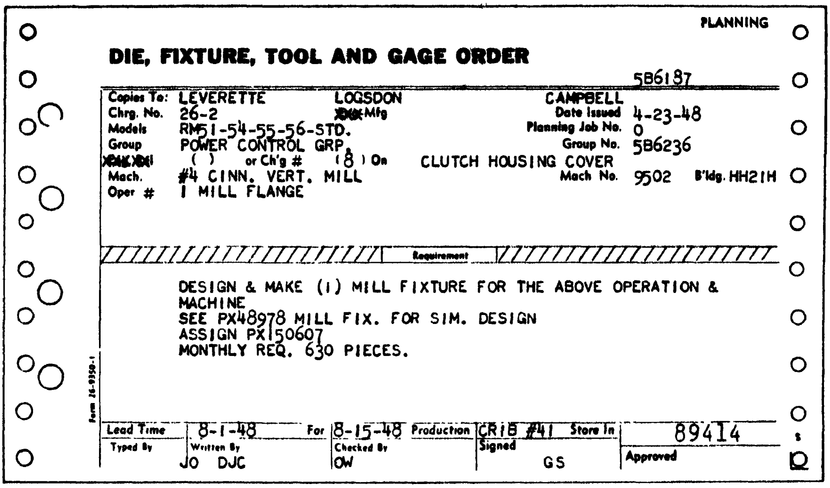
MACH. PREPARED	BASE TIME	QTY.	MODEL	DELIVER TO
DJC 4-22-48	EFT 4-22-48			
	MACH. RECORD			

SUPERSEDES SHEET DATED	ISSUE NO.	ORDER DATE	SCHED. LOT SIZE	SCHEDULE	QTY. STEEL OR CHG'S RECD
10-17-47					
MASTER TYPED	DATE COMPLETED FOREMAN'S SIG.	PART NO. 5B6187			

Fig. 95. One form of route sheet. (Courtesy Caterpillar Tractor Co., Peoria.)

tions, numbered in sequence. Each operation is briefly described and at the end of the description a symbol identifies the jig or fixture required. The machine and its location are identified for each operation by appropriate symbols. Standard time for each operation is also specified.

A common supplement to the route sheet is the tool order. Figure 96 shows a typical form, specifically the order for the milling fixture for the first operation of the route sheet of Fig. 95. The order identifies the project and operation and specifies the machine on which the fixture is to be used. A convenient means of designating the planned characteristics of a tool is to refer to a corresponding design, as is done in the tool order of Fig. 96 in the sentence: "See PX48978 mill. fixt. for sim. design."



PLANNING

DIE, FIXTURE, TOOL AND GAGE ORDER

5B6187

Copies To: LEVERETTE LOGSDON CAMPBELL
Chrg. No. 26-2 Mfg
Date Issued 4-23-48
Models RM51-54-55-56-STD.
Planning Job No. 0
Group POWER CONTROL GRP.
Group No. 5B6236
( ) or Ch'g # (8) On CLUTCH HOUSING COVER
Mach. #4 CINN. VERT. MILL
Mach No. 9502 B'ldg. HH21H
Oper # 1 MILL FLANGE

Requirement

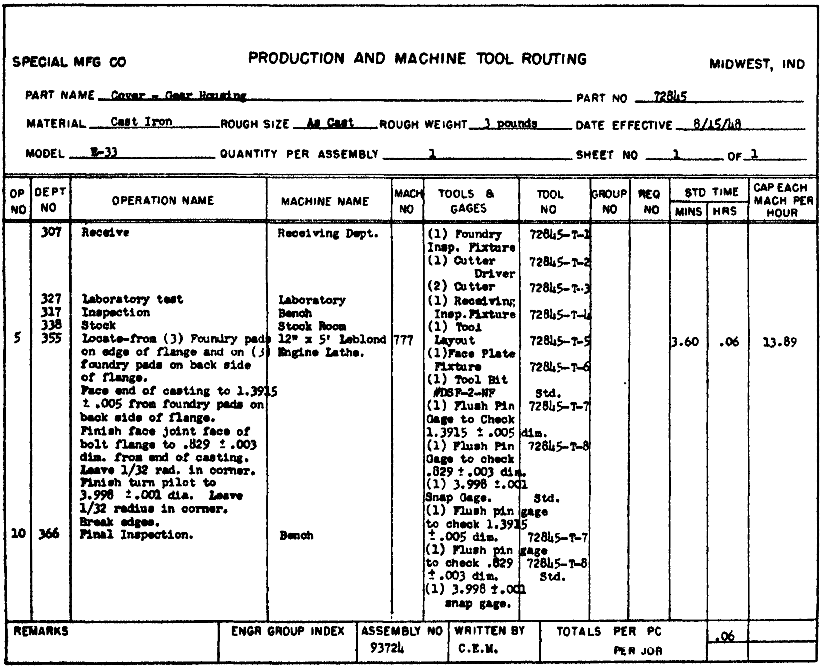
DESIGN & MAKE (1) MILL FIXTURE FOR THE ABOVE OPERATION & MACHINE
SEE PX48978 MILL FIX. FOR SIM. DESIGN
ASSIGN PX150607
MONTHLY REQ. 630 PIECES.

Form 26-9350-1

Lead Time 8-1-48 For 8-15-48 Production CRIB #41 Store In 89414
Typed By
Written By JO DJC
Checked By OW
Signed GS
Approved

Fig. 96. A typical tool order. (Courtesy Caterpillar Tractor Co., Peoria.)

Figure 97 illustrates a more detailed form of routing than that of Fig. 95, and represents a type found in some high production industries and in certain plants where the product, like aircraft engines, calls for exceptional accuracy. The description of each operation includes a statement of the locating surfaces and specifies the dimension and the tolerance of each cut. The machine and all tools, fixtures, and gages are specifically described. Much uncertainty and misunderstanding can be avoided by specifying physical items objectively and explicitly. As an example a description of "(1) adjustable snap gage for 1.0625 $^{+.003}_{-.000}$ dia." leaves nothing to the imagination.



SPECIAL MFG CO PRODUCTION AND MACHINE TOOL ROUTING MIDWEST, IND

PART NAME Cover - Gear Housing PART NO 72845
MATERIAL Cast Iron ROUGH SIZE As Cast ROUGH WEIGHT 3 pounds DATE EFFECTIVE 8/15/48
MODEL E-33 QUANTITY PER ASSEMBLY 1 SHEET NO 1 OF 1

OP NO	DEPT NO	OPERATION NAME	MACHINE NAME	MACH NO	TOOLS & GAGES	TOOL NO	GROUP NO	REQ NO	STD TIME MINS	STD TIME HRS	CAP EACH MACH PER HOUR
	307	Receive	Receiving Dept.		(1) Foundry Insp. Fixture (1) Cutter Driver (2) Cutter	72845-T-1 72845-T-2 72845-T-3					
	327	Laboratory test	Laboratory		(1) Receiving Insp. Fixture	72845-T-4					
	317	Inspection	Bench								
	338	Stock	Stock Room		(1) Tool Layout	72845-T-5					
5	355	Locate-from (3) Foundry pads on edge of flange and on (3) foundry pads on back side of flange. Face end of casting to 1.3915 ± .005 from foundry pads on back side of flange. Finish face joint face of bolt flange to .829 ± .003 dim. from end of casting. Leave 1/32 rad. in corner. Finish turn pilot to 3.998 ± .001 dia. Leave 1/32 radius in corner. Break edges.	12" x 5' Leblond Engine Lathe.	777	(1) Face Plate Fixture (1) Tool Bit #DSF-2-NF (1) Flush Pin Gage to Check 1.3915 ± .005 dim. (1) Flush Pin Gage to check .829 ± .003 dim. (1) 3.998 ±.001 Snap Gage.	72845-T-6 Std. 72845-T-7 72845-T-8 Std.			3.60	.06	13.89
10	366	Final Inspection.	Bench		(1) Flush pin gage to check 1.3915 ±.005 dim. (1) Flush pin gage to check .829 ±.003 dim. (1) 3.998 ±.001 snap gage.	72845-T-7 72845-T-8 Std.					

REMARKS	ENGR GROUP INDEX	ASSEMBLY NO	WRITTEN BY	TOTALS		
		93724	C.E.M.	PER PC	.06	
				PER JOB		

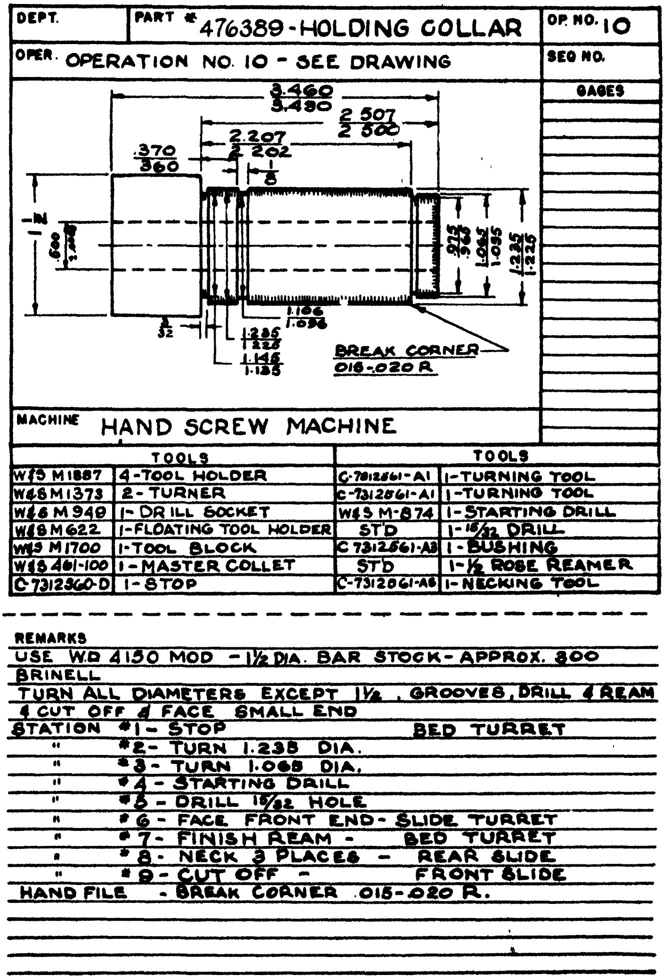
Fig. 97. Another type of routing.

Operation instruction sheets

Sometimes it is desirable to give detailed instructions concerning the conduct of the various operations in a process. These directions would clutter the route sheet and detract from its clarity. To tell how to do the work, operation or instruction sheets are written for each operation and supplement the routing. They may be called just instruction sheets. One type of operation instruction sheet is shown in Fig. 98. A sketch high-lighting the particular operation is a customary part of these sheets.

Details of expression

The forms that have just been presented are typical of those used to express process and tool plans. The forms are not the plans, but are convenient "tools" for expressing the plans. In Chap. 7 an out-


3.460
3.480
2 507
2 500
2.207
2 202
.370
360
1/8
.600
1.000
1/32
1.106
1.096
1.235
1.225
1.145
1.135
.975
.965
1.065
1.055
1.235
1.225
BREAK CORNER
015-.020 R

DEPT.	PART # 476389-HOLDING COLLAR	OP. NO. 10
OPER. OPERATION NO. 10 - SEE DRAWING		SEQ NO.
		GAGES
MACHINE HAND SCREW MACHINE		

TOOLS		TOOLS	
W&S M1887	4-TOOL HOLDER	C-7312561-A1	1-TURNING TOOL
W&S M1373	2-TURNER	C-7312561-A1	1-TURNING TOOL
W&S M949	1-DRILL SOCKET	W&S M-874	1-STARTING DRILL
W&S M622	1-FLOATING TOOL HOLDER	STD	1-15/32 DRILL
W&S M1700	1-TOOL BLOCK	C 7312561-A3	1-BUSHING
W&S 461-100	1-MASTER COLLET	STD	1-1/2 ROSE REAMER
C-7312560-D	1-STOP	C-7312061-A6	1-NECKING TOOL

REMARKS
USE W.D 4150 MOD - 1½ DIA. BAR STOCK - APPROX. 300
BRINELL
TURN ALL DIAMETERS EXCEPT 1½, GROOVES, DRILL & REAM
& CUT OFF & FACE SMALL END
STATION #1 - STOP BED TURRET
" #2 - TURN 1.235 DIA.
" #3 - TURN 1.065 DIA.
" #4 - STARTING DRILL
" #5 - DRILL 15/32 HOLE
" #6 - FACE FRONT END - SLIDE TURRET
" #7 - FINISH REAM - BED TURRET
" #8 - NECK 3 PLACES - REAR SLIDE
" #9 - CUT OFF - FRONT SLIDE
HAND FILE - BREAK CORNER .015-.020 R.

Fig. 98. An operation or instruction sheet. (From Owen, *Introduction to Tool Engineering*, p. 50, Prentice-Hall, 1948.)

line is given of the contents of a process and tool plan to satisfy the principles of manufacturing. That outline should be compared point by point with the forms, as it is the basis on which forms to meet any specific system can be designed.

The first group of items comprising a plan are those to identify the process. Some of these items are applicable only to certain situations, like the item for code numbers. Others are essential for all plans and include:

1. The name and number of the part to be produced, which appears on all the forms.
2. The quantity or lot size, indicated on the routing forms. In the case of the production and machine tool routing, this information is brought out by the model number specified; the model is subject to a definite production program.
3. The material specifications, shown on the two routings and the operation instruction sheet.
4. The model or assembly number, indicated on all but the instruction sheet. Reference can be made to the routings that accompany instruction sheets for this information.
5. The date on which the project becomes effective shown on all but the instruction sheet. When a plan is superseded, that information may be added to the routings.

The second group of items in the process and tool plan deal with the division of labor. These items are associated with the routing forms and appear there in the listing of operations. Consecutive operations may be numbered in single digits (1, 2, 3, 4, . . .) or in multiple digits (10, 20, 30, 40, . . .). The latter have an advantage, because operations can be inserted later and given in between numbers without it being necessary to renumber the entire series. An operation added between the second and third would have to be 2a, 2b, etc., as an alternative to changing all the numbers if single digits were used. This insertion could be numbered 25, leaving room on both sides for still other additions, if multiple digits were used.

The third group of items for a process and tool plan includes those related to the principles of interchangeable manufacture and control of quality. The extent to which the use of these principles is necessary varies with specific conditions. Production in which dimensional accuracy is of little concern may need scant reference to these points. Locating surfaces are specified in the production and machine tool routing of Fig. 97 but are not mentioned in the planning-operation sheet of Fig. 95. Nominal dimensions are mentioned for some operations of Fig. 95, but tolerances as well as dimensions are specified in Fig. 97. In general, it is considered good practice to state specifications accurately to avoid any possible misunderstanding, although brevity should be sought where it does not compromise clarity.

The fourth group of items describing the equipment and its use normally receive attention on all planning forms. Here again exact statements are preferable. In the cases of machines and special tools, their numbers may be sufficient. The last item of this group, the instructions for setup, etc., consists of details appropriate for instruction sheets.

The performance requirements (represented by standard times and machine capacities) are usually entered on the routings by the standards or time study department. They may be estimated before production begins or determined later by actual studies.

Use of planning information

Planning records provide a medium for disseminating information throughout a manufacturing organization so that all may work in harmony. To illustrate this, Fig. 99 lists the main divisions of a process plan, which commonly are recorded and shows where each point of information is applicable within the organization.

The need of certain information for some functions is obvious, for others more obscure. For instance, consider the size, type, and kind of machine. The tool and gage designing department is concerned, since its designs must fit specific machines. Machine tools and equipment may have to be purchased, and exact information is necessary for intelligent procurement. The tool tryout department needs the information to be able to prove the tools on the proper machine; plant layout to be able to arrange the machines properly; plant engineering to be able to provide services at the right stations; scheduling and dispatching to be able to allot suitable machines to the job; and production supervision to be able to know what facilities to use to be able to take advantage of the preparation.

DIVISION OF PRODUCTION PLAN	FUNCTION										
	TOOL & GAGE DESIGNING	EQUIPMENT PROCURE–NENT AND BUYING	TOOL INSPECTION	TOOL TRYOUT	TOOL STORES	TIME & MOTION STUDY	PLANT LAYOUT	PLANT ENGINEERING	PRODUCTION SUPERVISION	PRODUCTION INSPECTION	SCHEDULING & DISPATCHING
General Identification of Process	x	x	x	x	x	x	x	x	x	x	x
Operation and Department Identification	x	x	x	x	x	x	x	x	x	x	x
Instructions for set up and Conduct of Individual Operations	x			x	x	x			x	x	
Locating and Clamping Points	x		x	x		x			x	x	
Specifications of Requirements of Each Operation	x			x		x			x	x	
Size, Type, and Kind of Machine for Each Operation	x	x		x		x	x	x	x		x
Machine Attachments and Accessories	x	x		x	x	x		x	x		x
Standard Tools, Gages, and Holding Devices	x	x		x	x	x			x		
Special Jigs, Fixtures, Cutting Tools, Dies and Gages	x	x	x	x	x	x			x		
Performance Requirements	x	x		x		x			x		x

Fig. 99. Uses for information contained in production plans.

FORMATION OF PROCESS AND TOOL PLANS

Qualifications

Process and tool planning involves the solution of a series of problems wherein a profitable compromise is sought from among a number of advantageous or detrimental factors to approach the most efficient method. Basic principles dictate the desirable general procedure, but the exigencies of each case make it a distinct problem in itself to which individual judgment and reasoning must be applied. Although a general outline can be given of the steps by which a plan is formed, it must be understood that very few specific applications will involve all the considerations which are possible. Some jobs are complex and have many ramifications; others are comparatively simple and have obvious solutions. Also many considerations are interconnected and cannot be resolved simply by themselves. An understanding of the logic of planning, however, is helpful in analyzing any process, although all plans ultimately must be fashioned in accordance with individual requirements.

Much of the credit for developing an analytical approach to process planning is due to Mr. L. C. Lander, Head of the Department of Industrial Engineering of the General Motors Institute.

An outline of procedure

The following is a general outline of the steps of process and tool planning:

1. Determine the requirements and conditions of the process.
    a. Ascertain what is to be done.
    b. Investigate and clarify obscure requirements and shortcomings in specifications.
    c. Study design of product for possible improvements.
    d. Determine form, size, and shape of raw material.
    e. Ascertain quantity to be made.
    f. Determine the most exacting requirements.
2. Determine the operations of the process.
    a. Classify requirements according to typical processes or procedures.
    b. Regroup requirements according to specialties.
    c. Select suitable machines to combine similar activities into operations.

3. Determine the proper sequence of operations.
   a. Establish end points of process.
   b. Place operations according to their characteristics.
4. Determine how the part is to be located and held in each operation.
   a. Find the best locating spots on the part.
   b. Determine the clamping surfaces and forces.
   c. Choose suitable locators.
   d. Select clamping devices to satisfy conditions.
5. Determine how to keep errors within required limits with the least expense.
   a. Specify features of machines and tools for required performance.
   b. Estimate whether each operation as planned is capable of producing required results.
   c. Check effect of operations on each other, stock allowances, and accumulations of errors to make sure that the combined operations will, in the end, produce good parts.
6. Make provisions for measuring and gaging the results obtained.
   a. Specify equipment consistent with the degree of accuracy required.

The remaining chapters of this text will explain and elaborate on these steps of process and tool planning. It is suggested that, as each topic is taken up, reference be made to this outline to identify the place of the topic in the general scheme.

SUMMARY

The ways of expressing process and tool plans range from the purely oral to highly refined systems of recording data. Common forms used are route sheets, tool orders, and operation sheets. In general, a routing tells what is to be done, a tool order specifies the features of a tool to conform to the plan of the routing, and an operation instruction sheet is an adjunct to a routing, telling how an operation is to be done. Altogether, the forms used in any case should reflect the process and tool plan intended as far as the circumstances warrant.

Planning forms are media for transmitting the plans of production throughout an organization to harmonize the activities of all who contribute to the production effort.

The formation of a process and tool plan involves a series of steps. The first is to determine what must be done. Succeeding steps ascertain how the job can be done most efficiently through division of labor, use of the principles of interchangeable manufacture, use of tools, and control of quality. In the last step the provisions for measuring the results are considered.

QUESTIONS

1. What considerations dictate the extent to which process and tool plans are manifested?

2. Describe a routing or route sheet.

3. Describe a tool order.

4. Describe an operation or instruction sheet.

5. What specific items of a process and tool plan as listed in Chap. 7 are included in each of the following typical forms: (a) the planning operation sheet of Fig. 95, (b) the tool order of Fig. 96, (c) the production and machine tool routing of Fig. 97, (d) the operation instruction sheet of Fig. 98.

6. Design a route sheet form for a shop producing special tools and machinery.

7. Design route sheet, tool order, and operation sheet forms for an aircraft plant producing in fairly large quantities. It is desirable to plan for skills of as low an order as feasible in production.

8. The chart of Fig. 99 shows where the principal points of information in production plans are used in a typical organization. Tell why each of the following items is useful in the departments checked for it: (a) operation and department identification, (b) instructions for setup and conduct of individual operations, (c) locating and clamping points, (d) specifications of requirements of each operation, (e) size, type, and kind of machine for each operation, (f) machine attachments and accessories, (g) standard tools, gages, and holding devices, (h) special jigs, fixtures, cutting tools, dies, and gages.

9. List the principal steps in the formation of a process and tool plan.

10. What does a determination of the requirements and conditions of a process involve?

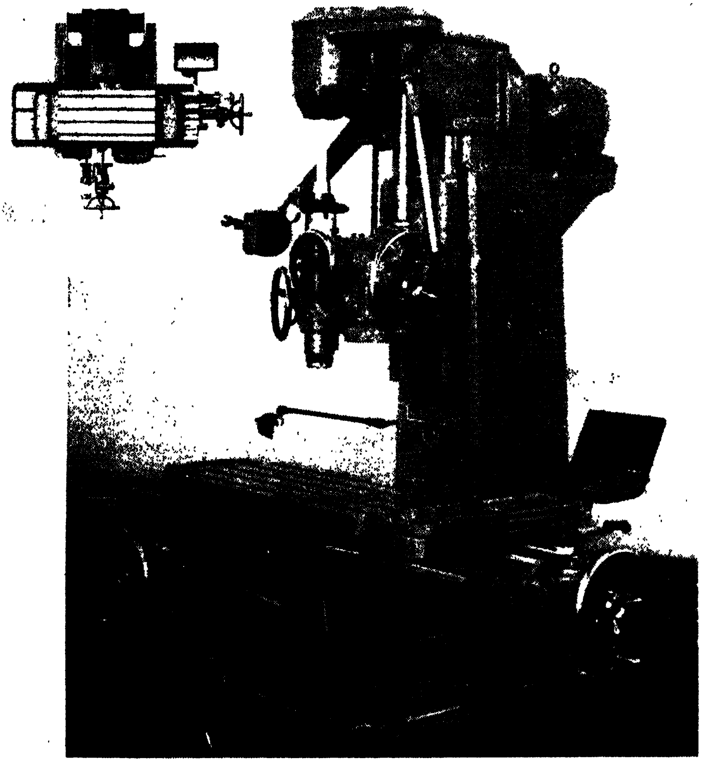


Fig. 100. A jig-boring machine for locating holes accurately. The table is carried on a saddle, which is mounted on the base. The inset shows a cut-away view of the top of the table and saddle on the base. The table is moved longitudinally and transversely by screws, through manipulation of the two handwheels, but is positioned by means of the ten-thousandth dial indicators and measuring instruments or length gages. These instruments are stored conveniently in the box mounted at the right rear of the machine.

The important principle of this machine is that it does not depend upon the leadscrews for setting, as they inevitably contain inherent errors and deteriorate from wear, nor upon other machine members that must necessarily deflect under load, but derives its accuracy from the precision measuring instruments of simple form, which are not subjected to appreciable stresses and wear. The indicators, in effect, serve as light spring balances to assure that the loading upon the instruments is constant for all settings and that uniform conditions are adhered to in changing from one setting to another. (Courtesy of Pratt and Whitney Div., Niles Bement Pond Co., West Hartford, Conn.)

9 PRINCIPLES OF DIMENSIONING

WHY DIMENSIONS AND TOLERANCES ARE IMPORTANT TO TOOL ENGINEERING

The importance of dimensions

Faulty dimensioning is one of the chief causes of manufacturing difficulties. This is especially evident in the initial stages of production, but even over long periods dimensional deficiencies may be so serious as to hinder production efforts almost interminably. Dimensions provide the foundation for interchangeable manufacture; they prescribe the physical requirements that must be fulfilled in production if functional utility of a product is to be realized. If requirements are not precisely described, they cannot be fulfilled, and the system inevitably fails. From product design, through production planning, to the last step of manufacture, dimensions are the criteria by which successful achievement can be judged.

For manufacture, the component parts of a mechanism are usually depicted by dimensioned drawings, prepared by the product engineering division of an organization. A competent tool engineer, however, must be able to appraise the adequacy of the dimensioning by which his efforts are directed and know whether the information furnished him is sufficient. He cannot hope to perform efficiently if handicapped by unnecessarily difficult requirements, and his efforts are futile if directed to providing means for producing parts, no matter how skillfully, if the specifications for those parts are misleading. In turn, the specifications that he prepares, like routings and tool designs, must be based upon the rules of dimensioning if they are to be successful.

The penalties of improper dimensioning

Drawings may be made without adequate regard for manufacturing requirements and limitations. Many such drawings depict idealized components that can never be realized in physical form. Dimensions and some limits may be given, but too often drawings fail to specify completely the necessary conditions for interchangeability and proper functioning.

A flagrant example of the difficulties ensuing from inadequate dimensioning was uncovered at the time of the urgent expansion of gun-manufacturing facilities during the Second World War. An old and well established firm manufacturing small arms was called upon to increase its output substantially. New machines and personnel were added to the plant. They began to make parts in accordance with the component drawings on file. Then it was discovered that the parts made to the drawings would not fit together, and even those that would go together would not function. The plant had been making arms successfully for many years, and an investigation naturally was conducted to ascertain why the production of guns should be suddenly stalemated. All parts were found conforming to specifications, so obviously the specifications were at fault. Then it was discovered that the inadequate dimensioning had never really been taken seriously. When guns were made in small quantities, the craftsmen employed had devised means, under less pressing circumstances, of overcoming the deficiencies. All over the plant individuals, whose fathers and grandfathers had preceded them in similar capacities, had sample pieces that were used as masters to which to form new pieces. When newcomers tried to duplicate the results, with only the guidance of the faulty drawings, their efforts were fruitless.

Although the foregoing may appear to be exceptional, it actually only illustrates to a marked degree the difficulties and disorders which are common in many industrial projects. Shortcomings in dimensional specifications are far from uncommon and really become evident when components reach assembly and test floors. Then, it may be found that some parts will not assemble without alterations; vital surfaces may be outside limits necessary to avoid binding and freezing; other surfaces within limits fit too loosely. A few assemblies may be completed, but their mortality under test is excessive. Of course, this condition must be corrected, and usually is to some extent, but not without backtracking, changing, and excessive expense, which could have been avoided in the first place with competent dimensional planning.

Elementary considerations

Dimensions describe physical requirements that are based upon functional needs and manufacturing practicalities. An essential part of any dimension is its tolerance. Thus one of the first demands of adequate dimensioning is that tolerances be set properly and shown clearly. For that purpose we shall consider:

1. Ways of writing tolerances. There are a number of ways of expressing tolerances. Each has advantages under certain conditions.
2. Factors governing the selection of tolerances. Economy in manufacture is possible because small tolerances are not necessary for most dimensions. It is as important to recognize dimensions that do not need restraint, as it is to be able to apply the proper tolerances when they must be close.

Through any medium, it is difficult to convey an idea from one person's mind to another without the one receiving the information interpreting it in accordance with his own impressions and convictions. In the case of language, rules have been evolved to promote clarity and precision of expression. Also, for dimensions, experience has shown that the observance of certain principles is necessary if confusion is to be avoided. Among these are:

1. A point should be located by only one dimension in a straight line.
2. Points, lines, or planes should be dimensioned directly to others with which they have a specific relationship.
3. A part must be dimensioned in three co-ordinate directions, and the dimensions given must correspond to functional requirements.
4. The initial or leading figure of a dimension should be the exact amount it would be desirable to have if it were possible to work without tolerance.
5. No more than one dimension should be given between any two points.

These rules will be explained in the second part of this chapter.

In some respects, dimensioning of tool drawings may differ from practice for production parts. The reasons for that will be pointed out.

WAYS OF WRITING TOLERANCES

Definitions

As a basis for discussion of this subject, the meanings of the following terms are important.

Tolerance is the unavoidable variation permitted in a dimension for economical production.

Allowance is the intentional least difference between the corresponding dimensions of two mating parts. It is the least clearance or most interference between mating surfaces.

Basic size is the theoretical or nominal standard size from which variations are made.

Limits are the extreme permissible values of a dimension or group of dimensions.

Standard size refers to a recognized or accepted size corresponding to subdivisions of a recognized unit of length. The common fractions of an inch are called standard sizes.

Bilateral tolerances

The bilateral form of tolerance states a dimension with a permissible variation in both directions. A typical bilateral tolerance is 1.000 ± 0.001 in. The plus and minus values are not always equal; that is, the specified size is not always the mean size. For example, a dimension may appear as $1.0000 \begin{smallmatrix}+0.0015\\-0.0005\end{smallmatrix}$ in.

The bilateral form is the oldest and is widely used, no doubt in a large part because of custom. Advocates of the form have claimed that it favors the production of a dimension on the average closer to the specified or ideal size. In other words, it designates a figure at which the workman is supposed to aim. This presupposes that the mechanic is working to a size that he measures and not, as is usually the case in production, to a range that he gages without ascertaining the exact value obtained. Also, such a goal has little or no advantage if the specified dimension is not the most desirable within the tolerance. In the case of a shaft, the maximum metal size, which leaves the most material on the part, may be the most desirable. In that case, a bilateral tolerance offers no advantage. On the other hand, a series of parts in an assembly may be subjected to the least stack-up and displacement if their respective dimensions are at their mean values. For that purpose bilateral tolerances may be advantageous.

An objection sometimes made to the use of bilateral tolerances for diametral dimensions is that they do not promote the most efficient use of plug gages for standard hole sizes. As an illustration, a 1.000-in. diameter hole requires a different set of go and no-go plug gages for every different set of bilateral tolerances. This situation may be relieved if one limit is fixed, however.

Unilateral tolerances

If the tolerance of a dimension is applied all in one direction, it is a unilateral tolerance. The stated dimension is then spoken of as the limiting size, as well as the basic size. In this form, a dimension might be specified as $1.000 \begin{smallmatrix} +0.002 \\ -0.000 \end{smallmatrix}$ in. An evident characteristic is that a unilateral tolerance definitely specifies a dimension beyond which deviation is not tolerated in one direction and prescribes a working zone in the other direction. If the specified limiting dimension is a standard size, then it can be checked readily with reliable commercial standard gages. Furthermore, if a change in tolerance on the working side of the standard size is found necessary, only one gage needs to be changed. This is worth consideration where fixed size plug or ring gages are employed.

Limiting dimensions

In quantity production, usually each operation is completely tooled and supplied with gages. The part drawings seldom reach the machine and inspection floors, but rather serve to guide the tool engineers who plan and design the tools and gages. Most tools and gages, under such circumstances, are selected or made to conform to the limits that must be maintained. To suit those purposes, limiting dimensions are advantageous. Typical of that form is the dimension 1.002 – 1.000.

Suitability of tolerance forms

Each tolerance form has certain appropriate usages in accordance with its advantages. Widely accepted practice makes use of all forms to reflect specific conditions. These are:

1. *Conditions of the design.* Most dimensions do not require close confinement and can be quite adequately expressed by common fractions or decimals to one or two places without individual tolerances. For such designations, standard practice regulations within the organization or a printed note on the drawing form may specify a nominal tolerance, bilaterally, of $\pm\frac{1}{64}$ in., ±0.010 in., or ±0.020 in. for machined surfaces. For castings, a tolerance of $\pm\frac{1}{16}$ in. or some other suitable amount may be specified.

Limiting dimensions are sometimes used to highlight the most exacting dimensions of a part. Thus, a drawing may show the dimensions that do not require close confinement with bilateral or unilateral tolerances, but close dimensions by their limiting figures.

One thought is to employ tolerance forms to indicate desirable tendencies; thus, dimensions from which deviation in either direction is equally dangerous (or to look at it from the other point of view, dimensions for which deviation in either direction is unimportant) may have such circumstances evinced by bilateral tolerances. The locations of hole centers and of the components of welded assemblies are frequently dimensioned on that basis. On the other hand, deviation in one direction from a standard dimension, but not in the other, may be permissible, and that situation is pointed out by unilateral tolerances, most suitable for diametral dimensions.

2. *Characteristics of the particular operation or process by which*

TABLE 6

TOLERANCES

Size of Hole	*Tolerance*
#80 (0.0135)—#13 (0.185) inclusive	+0.003 −0.002
$\frac{3}{16}$ (.1875)—D (0.245) inclusive	+0.004 −0.002
$\frac{1}{4}$ (.250)—3.4 (.750) inclusive	+0.005 −0.002
$\frac{49}{64}$ (.7656)—1 (1.000) inclusive	+0.007 −0.002
$1\frac{1}{64}$ (1.0156)—2 (2.000) inclusive	+0.010 −0.003

Uncontrolled holes for lightening, bolt clearances, and oil passages, etc., may have a tolerance of ±0.010.

Holes for drive fit pins must be held to ±0.001.

the dimension is to be produced. For example, drills almost always produce a hole diameter larger than nominal, and a heavier tolerance is desirable on the positive side. Table 6 shows practice for drilled holes followed in a large engine plant. The tolerances shown in the table are applicable to drilled holes of controlled sizes, such as cotter pin, oil metering, jet, rivet, and tap holes.

In contrast, punched holes have a tendency to become smaller as the punch wears, and common practice is to specify the hole diameters with a unilateral tolerance in the negative direction. A drawing on which several tolerance forms are used concomitantly where applicable is that of Fig. 135.

Standard hole and standard shaft practices

Up to this point tolerances have been treated as means of expression, but they may also serve as the media for systems of designing and planning. Unilateral tolerances have been associated in many minds with routines of keeping constant an extreme size of one member of a pair. This concept is carried out in two systems known as *standard hole practice* and *standard shaft practice.* A longer name for standard hole practice is "uniform minimum hole system."

Holes in soft materials are commonly finished by reaming. Reamers are available commercially in standard fixed sizes and produce holes of a slightly larger dimension. It is also common practice to gage holes with fixed plugs. In contrast, external surfaces, like on shafts, are usually turned or ground, so that adjustments to suit variations are easy, and can be checked readily with adjustable snap gages. To take advantage of these circumstances, standard hole practice places the lower limit of the internal surface, the hole, at the basic size of the fit. Tolerance for the hole is applied in a positive direction. Allowance is provided by varying the upper limit of the shaft, from which tolerance is extended in a negative direction.

Figure 101 illustrates the application of standard hole practice to two different cases, each of 1-in. nominal size. In both instances, the minimum size of the hole is 1.000-in. Since the allowances are not alike, the maximum or specified sizes of the shafts are different.

Standard hole practice allows the use of a single set of reamers or comparable tools and a single set of "go" plug gages for all fits of a nominal size. If tolerances must be changed, after production has started, only the "no-go" gages need be replaced. Furthermore, a standard reamer cuts near the small size of the hole, leaving the most material for wear in service.

Sometimes the advantages of a standard hole practice are more than offset by other circumstances. An example is a shaft on which several external members must be assembled, each with a different fit. It is more economical in some instances to use a standard shaft and vary the sizes of the holes as required, rather than machine a number of diameters on a shaft. Especially is this true if the holes are ground to size. Standard shafting is made to a basic size with a negative tolerance. Thus, the maximum or specified size of the shaft is placed at the basic size in standard shaft practice. For this practice, the shaft of Fig. 101A would be dimensioned 1.000 $^{+0.000}_{-0.001}$ in. and the hole 1.001 $^{+0.001}_{-0.000}$ in.

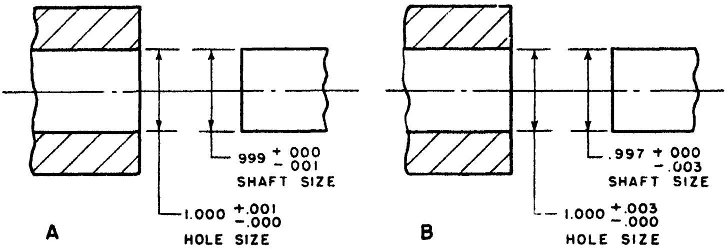


Fig. 101. (A) A running fit. The 1-in. nominal size is dimensioned according to standard hole practice. The hole and shaft each have a tolerance of 0.001 in., and the allowance is 0.001 in. (B) A loose fit. The 1-in. nominal size is dimensioned according to standard hole practice. The hole and shaft each have a tolerance of 0.003 in. and the allowance is 0.003 in.

Maximum hole practice

Some years ago an investigation was made in various plants of the General Motors Corporation[1] to determine how much a reamer would actually cut over its own size in such materials as cast iron, steel, bronze, and aluminum. About 3500 holes up to 1½-in. diameter were measured with carefully fitted expanding plug gages.

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[1] *General Motors Standards,* Vol. III, pages B-3, 4, 5. Detroit, Mich.: The General Motors Corp., 1930.

All reamers were measured at the same time. It was found that under normal conditions the large majority of reamers cut less than 0.0007 in. larger than their own diameter, regardless of size or material.

On the basis of the findings for reamers a maximum hole practice was proposed for which the large size of any hole was set at 0.0005 in. above basic. The minimum size of holes for six classes of tolerances were fixed in steps below the maximum, in the direction of reamer wear, as shown in Fig. 102.

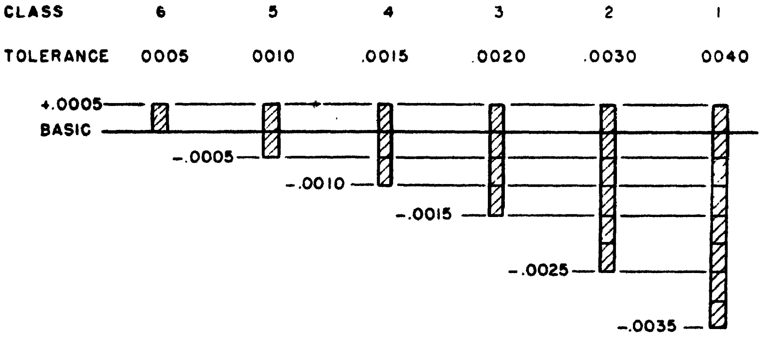

Fig. 102. Hole tolerances for maximum hole practice.

For maximum hole practice, the same no-go plug gage can be used for all classes of holes of one nominal size. As reamers wear, they can be transferred from one class to another.

THE SELECTION OF TOLERANCE

Service needs versus practical limitations

Fortunately the large majority of dimensions manufactured serve quite well with liberal tolerances. Normally, only a comparatively few dimensions in any assembly serve in functional fits, a circumstance that makes quantity production possible at low cost. The close dimensions are naturally those which must receive the most attention. If assurance is to be had that a dimension will be manufactured within limits suitable for functional needs, two considerations must be taken into account in finding the tolerance for it. They are:

1. The service needs of the part or article concerned.
2. The feasibility of producing the tolerance at a reasonable cost.

To illustrate these two considerations, their bearing upon two typical cases will now be considered.

Tolerance for running fit

For a running fit of a shaft in a bearing, there is a minimum clearance, the allowance, which provides room for lubrication and differences in thermal expansion of the pieces. This is dependent upon the type of lubrication and conditions of service. For the same fit, there is likewise a maximum clearance beyond which satisfactory alignment and stability are lost. If mating parts are made with maximum clearance, as soon as wear takes place the limit of satisfactory performance is exceeded. Consequently, the manufactured clearance of any set of parts must be somewhat less than the maximum clearance permissible for satisfactory functional performance.

Small tolerances insure close initial fits for mating parts, but necessitate high manufacturing costs. More liberal tolerances mean that some of the assemblies will probably be short-lived, but that fabrication costs will be lower. Theoretically, the most economical condition ensues from one set of tolerances providing the lowest average unit cost per hour of service. In practice, competitive conditions may dictate a unit cost above the minimum for the sake of a lower initial cost. On the other hand, for a quality product the convenience to the purchaser of long and carefree service may justify a higher initial cost.

A designer usually has the choice of a number of processes or types of operations for producing a pair of mating dimensions for a running fit. He must have at least an understanding of the tolerance available from each and its cost. The solution of the problem of finding the most suitable tolerances for the dimensions consists of determining the necessary allowance and maximum clearance, eliminating the prospective operations that apparently cannot meet the requirements, and comparing the remainder to ascertain the most propitious from the standpoint of ability to render the desired economic service. The tolerances assigned to the mating dimensions must conform to the limits to which the selected operations are expected to produce.

Tolerance for press fit

For any press fit there is an allowance offering the least amount of metal interference necessary to hold the mating parts together. Beyond that, there is a degree of interference that introduces maximum initial stresses into the material. Greater interference may be expected to cause failure. The range between the maximum and minimum interferences represents the sum of the combined tolerances of the mating parts. For the design to be successful, these tolerances must be realizable by operations within the economic range of the product.

Selective assembly

Where functional requirements impose close restrictions upon tolerances, an adjunct of interchangeable manufacture, called selective assembly, may be employed to reduce costs. By this system, a dimension that must be held very closely is given a wider variation for purposes of fabrication. The pieces are then segregated into groups according to the size of the dimension so that each group contains parts with the dimension within a range conforming to the variation permitted. The same procedure is followed with the mating parts which are added to form a unit. The only dimensions in the unit assembly requiring complete interchangeability are those by which the assembly comes into contact with still other parts. These external dimensions of the assembly usually need not be confined as closely as those matched by selective assembly but even if they must, the number of surfaces involved is less than if all critical dimensions of the unit assembly were made interchangeable.

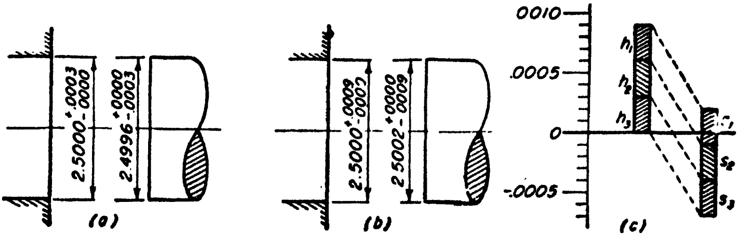

Fig. 103. Dimensioning for selective assembly. (From Spotts, *Design of Machine Elements*, p. 322, Prentice-Hall, 1948.)

Example 17: The hole and shaft of Fig. 103A have a tolerance of 0.0003 in. each, which is too close for economical production. Under the system of selective assembly, the parts may be made with a tolerance of 0.0009 in. each, as depicted in Fig. 103B. The pieces will then be sorted into three groups, each with a range of 0.0003 in., as indicated by the bar diagram of Fig. 103C. The holes in group h_1 are assembled with shafts in group S_1; the holes in group h_2 with shafts in group S_2; and the holes in group h_3 with shafts in group S_3. Obviously, selective assembly is a systematic process and not just trial and error.

Application of selective assembly

Ball bearings are manufactured by selective assembly. The variations in sizes of the inner race, balls, and outer race that make the difference between a snug and loose bearing are very small, of the order of one ten-thousandth of an inch. To reduce their cost, these components are manufactured more leniently and graded into groups. The bearings are assembled from comparable groups. Only the inside and outside diameters of each bearing need be finished to interchangeable dimensions. An incidental advantage of this system is that the manufacturer is able to arrange bearings suitable for various purposes by combining components from different groups. By that means three desirable classes are derived: a free running and loose bearing, a snug but free bearing, and a preloaded bearing for close constraint of a shaft or spindle.

Standard fits

Although there is an infinite number of possible different fits, experience has proven that relatively few classes and grades suffice for most applications. Workable classifications have been made to suit the needs of various industries and individual plants. For general purposes, the American Standards Association[2] has standardized fits into eight classes. That standard is summarized in Fig. 104. Detailed working tables of the tolerances and allowances for common dimensions are available in standard bulletins and handbooks.

As Fig. 104 shows, Class 1 gives the loosest fit with the most tolerances and is used where accuracy is not essential, for such products as agricultural and mining machinery. The liberal allowances and tolerances of Class 2 provide freedom where speeds or pressures in service are high. Class 3 is intended for comparatively low speeds and pressures, for sliding fits and the more accurate machine tool and automotive fits. Class 4 is a snug fit and requires considerable precision. Selective assembly is usually required for Class 5, called a wringing fit. Class 6 is a tight fit for more or less permanent assemblies, such as the fixed ends of studs for gears and pulleys. Considerable pressure is required to assemble parts for Class 7, called a medium-force fit. This is the tightest fit for holes in cast iron and is used for such parts as locomotive and car wheels, dynamo and motor armatures, and crank discs. Class 8 is a heavy force or shrink fit for steel holes.

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[2] *Tentative American Standard Tolerances, Allowances, and Gages for Metal Fits B4a-1925.* New York: American Standards Association.

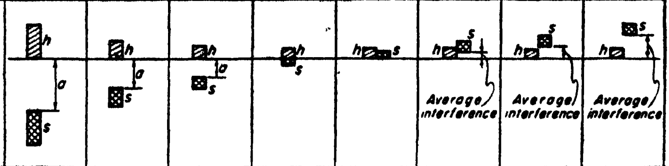
Class of Fit	1	2	3	4	5	6	7	8
Box Diagram (Basic hole system)								
Hole tolerance	$0.0025\sqrt[3]{d}$	$0.0013\sqrt[3]{d}$	$0.0008\sqrt[3]{d}$	$0.0006\sqrt[3]{d}$	$0.0006\sqrt[3]{d}$	$0.0006\sqrt[3]{d}$	$0.0006\sqrt[3]{d}$	$0.0006\sqrt[3]{d}$
Shaft tolerance	$0.0025\sqrt[3]{d}$	$0.0013\sqrt[3]{d}$	$0.0008\sqrt[3]{d}$	$0.0004\sqrt[3]{d}$	$0.0004\sqrt[3]{d}$	$0.0006\sqrt[3]{d}$	$0.0006\sqrt[3]{d}$	$0.0006\sqrt[3]{d}$
Allowance	$0.0025\sqrt[3]{d^2}$	$0.0014\sqrt[3]{d^2}$	$0.0009\sqrt[3]{d^2}$	0				
Av Interference					0	0.00025d	0.0005d	0.001d

Fig. 104. A.S.A.-B4a-1925, classification of cylindrical fits. (From Spotts, *Design of Machine Elements*, p. 330, Prentice-Hall, 1948.)

Classes 1 to 4 are clearance fits; Classes 7 and 8 are interference fits; but Classes 5 and 6 may give either clearance or interference if randomly assembled and are called transitional fits. The particular class of fit for any one application must be selected on the basis of the requirements of the case. Then from the formulas of Fig. 104 or from handbook tables, the proper allowance and tolerance can be selected for the diameter desired.

THE RULES OF DIMENSIONING

A point should be located by only one dimension in any one line

The first rule states in effect that a point, line, or surface can be held in production in relation to only one other point, line, or surface. This condition results from the nature of repetitive manufacture. The actions of tools are preset and fixed. A single tool for a surface may be set in relation to a locating or registering surface or in relation to another tool producing another surface in the same operation. A tool cannot be set successfully to two surfaces.

Figure 105-I shows a step block dimensioned in violation of the first rule. If *A* is the initial reference surface, then the dimensions prescribe that every other step (*B*, *C*, and *D*) must be finished in relation to two surfaces. For instance, surface *B* must be made to

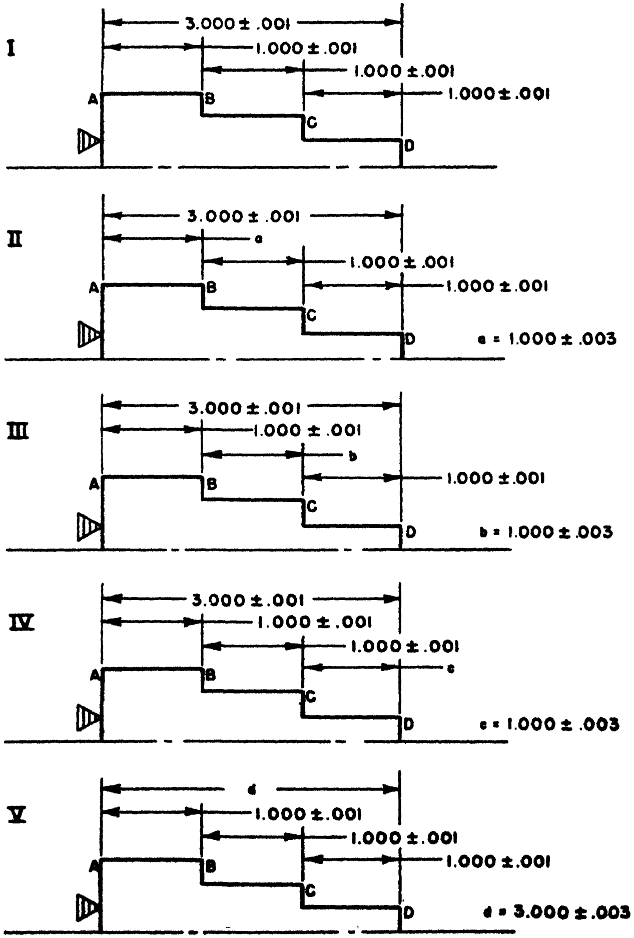


Fig. 105. Difficulties encountered if attempt is made to use more than one-dimensional series in the same straight line.

a dimension of 1.000 ± 0.001 in. from *A* and also to the same dimension from *C*, since *C* is fixed in relation to *A* through *D*. Views II through V of Fig. 105 show how the part may be dimensioned to agree with the first rule. The arrangement desirable for any specific case depends upon functional requirements. The dimensions designated as *a*, *b*, *c*, and *d* would be omitted from the actual drawing in each instance. The distances which *a*, *b*, *c*, and *d* represent will vary by ±0.003 in. Thus, in Fig. 105-II, surface *B* is machined to the 1.000 ± 0.001 dimension from *C* alone and is not held directly to *A*. Although *B* can be expected to lie within a distance of 1.000 ± 0.003 in. from *A*, that occurs as a resultant of the other dimensions and is not explicitly specified on a drawing.

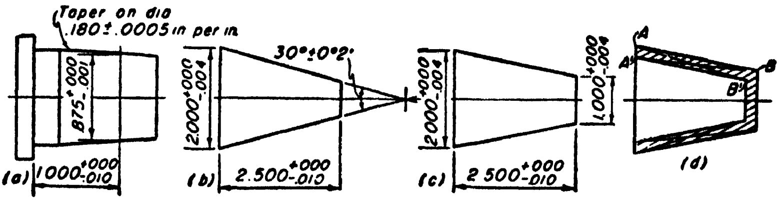


Fig. 106. Various methods of dimensioning tapers. (From Spotts, *Design of Machine Elements*, p. 327, Prentice-Hall, 1948.)

Taper Dimensions. The first rule has been illustrated by a simple case. It applies also to more complex forms, where trouble can be expected if attempts are made to apply tolerances to all dimensions. A taper is one such profile. In general, a taper can be fully defined by dimensions prescribing the amount of taper and the location and size of a diameter on the taper. Two ways of showing these three dimensions are shown in Fig. 106A and B. Strictly speaking, no tolerance is necessary on the taper or angle of Fig. 106A and B, and a compound tolerance is introduced by these tolerances. Wherever possible, they should be avoided, but this compound tolerance is permissible when the variation in the taper must be held to close limits.[3]

In Fig. 106C a method of dimensioning a taper is shown in direct violation of the first rule. Outside of the fact that it is extremely difficult to measure directly to the sharp edges, a number of widely variable results can be obtained from the layout. The tolerance zone permitted by the three toleranced dimensions is shown in Fig. 106D.

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[3] M. F. Spotts, *Design of Machine Elements*, page 326. New York: Prentice-Hall, Inc., 1948.

Dimensions should appear between related surfaces

If two surfaces, *A* and *B*, are each dimensioned to a surface *C* so that the tolerance of *AC* is $\pm a$ and the tolerance of *BC* is $\pm b$, the possible variation in the distance *AB* is the sum of the tolerances or $\pm(a + b)$. This is shown in Fig. 107. With this arrangement, a dimension may not be added between surfaces *A* and *B* for that would violate the first rule. This simple example illustrates the fact that two surfaces, which are not tied together directly by a dimension with tolerance, may vary in relation to each other by as much as the sum of the tolerances of all the dimensions from each surface to a common datum surface. Such a complex arrangement is not the most logical if a definite connection between the surfaces is intended. That is the reason for *the second rule* which states that points, lines, or surfaces should be dimensioned directly to others with which they have a specific relationship.

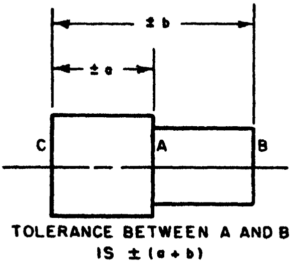


Fig. 107. An illustration of the second rule of dimensioning.

An illustration of tolerance accumulation is given in Fig. 108. In the upper sketch, with dimensions between steps with tolerances of ±0.005 in., the over-all variation in the length of the part may be ±0.015 in. With the piece dimensioned as it is in the lower figure, the variation between each face and the small end is the amount of the tolerance, ±0.005, but that between the large end and the faces is ±0.010 in. The figures by themselves carry no implications as to which form of dimensioning is preferable. That preference is based solely upon the circumstances of each particular application; that is, upon whichever form meets functional and productive requirements.

Practical considerations may sometimes modify the application of the second rule. The shaft of Fig. 109 is an example. It is desirable that the lightening hole dispose of as much excess material as possible, to minimize the weight of the shaft without weakening the member excessively by creating too thin a section at the shoulder. Theoretically, this condition can be controlled directly by dimensioning the depth of the hole with a tolerance in the manner shown in Fig. 109A, but such a dimension is rather difficult to gage. The dimensional arrangement shown in Fig. 109B is more convenient but presents the necessity of holding the tolerances of the two dimensions, *E* and *F*, closer than that required of *D*.

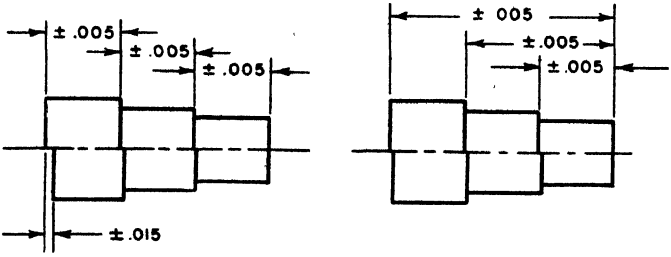


Fig. 108. Accumulation of tolerances.

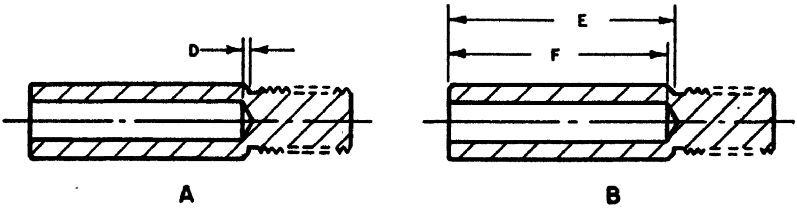


Fig. 109. (A) Theoretical way of dimensioning bottom of lightening hole to shoulder to insure adequate but not excessive wall thickness. From a practical standpoint the bottom of the hole is rather inaccessible from the shoulder. (B) A practical way of dimensioning. Dimensions *E* and *F* can be gaged readily, but their tolerances together must not exceed that of *D*.

A part must be defined in three co-ordinate directions

The following definitions of terms are relevant to the *third rule:*

1. *Datum planes* are imaginary or real surfaces to which various features of a part are related dimensionally. Preferably they should be real planes so that actual measurements can be made from them. For an object occupying space, three datum planes are usually necessary.

2. *Functional surfaces* are those which enter into the operation or location of the part in the mechanism.

3. *Clearance surfaces* are those that provide continuity in the part, but have no functional characteristics.

4. *Atmospheric surfaces* have no contact relationship nor proximity to surfaces of other parts of the mechanism.

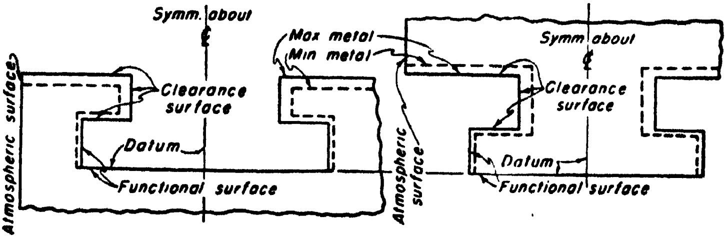


Fig. 110. Tolerance zones for T slide. (From Spotts, *Design of Machine Elements*, p. 325, Prentice-Hall, 1948.)

Figure 110 shows the functional, clearance, and atmospheric surfaces, as well as two datum planes each for two T-slide parts. The functional surfaces are those that maintain alignment as the two parts slide, one past the other. The clearance surfaces on one part are adjacent to those on the other part when the two parts are put together, but there must be clearance between those surfaces to avoid binding. The outside surfaces are the atmospheric ones.

The center planes of the parts of Fig. 110 are designated as datum planes. The manufacture and inspection of a part from such an imaginary plane may be very difficult. On the other hand, from the standpoint of design, such a datum plane may be advantageous. If it is possible to place two dowel holes in the part to mark the center plane, the conflict of interests may be resolved.

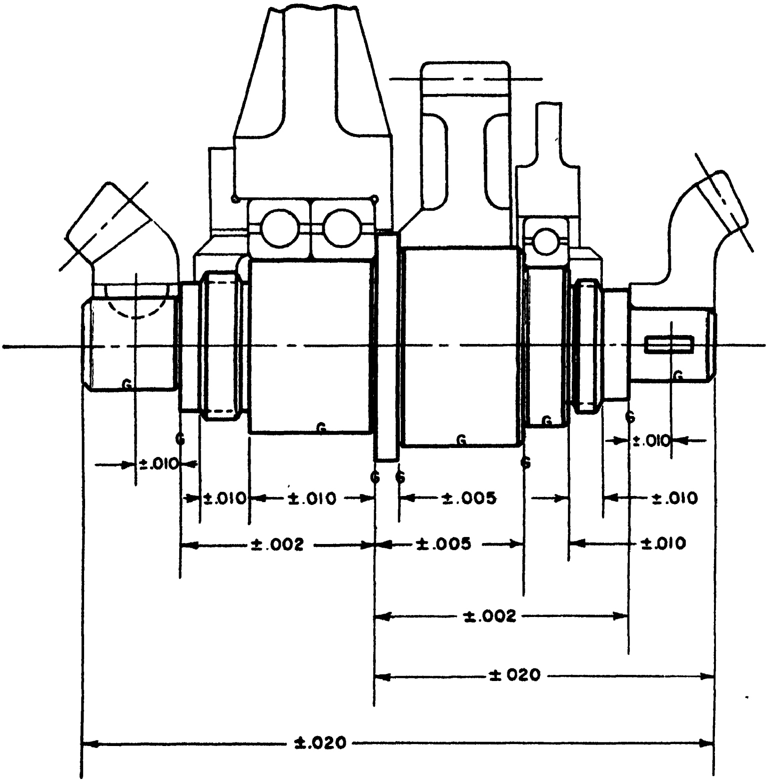
The definition of a part in three co-ordinate directions requires more than just placing dimensions in the three directions. It means also that the dimensions must appear in the three directions in such a way as to define the important features of a part. The second rule showed how the relationship between points or surfaces may be affected by the method of dimensioning. It did not specify what might be desirable relationships. The third rule points out that these relationships must be fully covered by dimensions in the way that suits the circumstances of each case.

The origin of critical surfaces. A part of a mechanism must be located in three co-ordinate directions if it is to perform a predictable function. The surfaces from which this location is derived are automatically functional in character. The other functional surfaces of the part obviously have specific relationships to the locating surfaces, and it follows from the second rule that they should be dimensioned directly to the locating surfaces. In other words, the locating surfaces are logical datum planes for the other functional surfaces of the piece. Furthermore, the tolerances of the functional dimensions must be relatively close to insure the required degree of performance.

The shaft of Fig. 111 is sketched in its functional position. Location is secured from the diameter and adjacent shoulder making contact with the double bearings. The other functional surfaces include the shoulders against which the contact faces of the bevel gears bear, the shoulder against which the hub face of the spur gear is pressed, the shoulder locating the single ball bearing, and their adjacent cylindrical surfaces. The shoulders are dimensioned in a complete drawing from the locating shoulder with comparatively close tolerances. The diameters would be dimensioned with tolerances, too. The respective cylindrical surfaces are related geometrically, and observance of that relationship is attested by a concentricity note. The diameters take care of two directions, and the length dimensions of the third direction.

Clearance surfaces likewise may be related directly to the locating surfaces, to insure that they do not make contact with other parts and thus interfere with proper location. However, the relationship of certain clearance surfaces with functional surfaces other than the locators may be more pertinent; and it may be desirable, and usually is permissible, to dimension the clearance surfaces to suit, with provision for indirect dimensional connection between clearance and locating surfaces.

Typical of the clearance surfaces of Fig. 111 are the Woodruff keyways. It is only important for their position that they do not come too close to the shoulders and that they fall within the ends of the shaft. For that reason, they are dimensioned to the adjacent shoulders, which are functional but not datum surfaces. The same can be said of other clearance surfaces on the part.



ALL DIAMETERS MARKED "G" MUST BE CONCENTRIC AND EACH MUST BE SQUARE WITH ITS ADJACENT SHOULDER MARKED "G" WITHIN .0005 INCH TOTAL INDICATOR READING.

Fig. 111. A shaft depicted in its functional environment to show how its location affects its dimensional tolerances.

Atmospheric surfaces have no functional obligation, but they are normally connected, if only indirectly, with the datum planes, with liberal tolerances, to knit together the features of the part.

The ends of the shaft of Fig. 111 are atmospheric surfaces and, therefore, have no particular relationship with other surfaces, and one is tied in with the locating surfaces only to follow the general pattern. There is, however, a relationship between the two ends, and that is the over-all length of the piece. An over-all dimension is convenient for ascertaining stock length, machine capacity, etc., and should always be specified. If the sum of component dimensions comprises the total length of the piece, then a dimension between terminal points may be given as a reference without tolerance.

The choice of functional locating surfaces as datum planes enhances their suitability as locating and gaging areas in manufacturing. It is obviously advantageous to employ the same surfaces for locating a piece when it is fabricated as will position it in service. The principal surfaces used for location in manufacturing are called critical surfaces. They will be referred to frequently. Their primary concern with the function of a part should not be forgotten.

The most desirable size should be specified as the size of a dimension

A bearing and shaft for a running fit are most desirable at their maximum metal sizes. If the hole is at its minimum size and the shaft at its maximum when they are assembled, the clearance between them will be the allowance and each will contain the maximum possible amount of material for wear. If this combination is dimensioned with unilateral tolerances, then the size of the hole is most seemingly given at its minimum size with the tolerance specified in the positive direction, and the shaft at its maximum size with its tolerance in the negative direction. Thus, notice is given plainly of the optimum condition.

For an example, a nominal 1-in. hole and shaft with allowance of 0.001 in. and tolerance for each of 0.001 in. would be specified as:

$$\text{Hole size} \quad 1.000\,{}^{+0.001}_{-0.000}$$

$$\text{Shaft size} \quad 0.999\,{}^{+0.000}_{-0.001}$$

The same procedure is followed with limiting dimensions. In the case of the hole, the lower limit leads or is placed above the upper limit, and the reverse applies to the shaft. For the same fit, by limiting dimensions:

$$\text{Hole size } \frac{1.000}{1.001} \quad \text{or} \quad 1.000 - 1.001$$

$$\text{Shaft size } \frac{0.999}{0.998} \quad \text{or} \quad 0.999 - 0.998$$

This rule may imply but does not dictate invariably any particular tolerance form. That depends upon the exigency of each application. *The fourth rule* merely specifies that the initial or leading figures of each dimension should be the exact amount which would be desirable if tolerances were not necessary. The tolerances must then be applied to recede into less desirable, but not prohibited, zones. In the case of a running fit, as has just been shown, the desirable limits are those of the allowance, and the tolerance of each member may recede in only one direction from that status. For other applications, different circumstances prevail.

For assemblies like that of Fig. 111 the mean value for each dimension may be the most favorable. In such a case each dimension carries tolerance in both directions; in other words, bilateral tolerances are employed.

Only one dimension between two points

The same dimension between two points, perhaps each in a different view, may appear in a drawing intentionally or through error. It may be the intention of the draftsman to make the dimension easier to find. Such advantage as may be derived is of questionable value in view of the trouble that may result, particularly if there is need to change the dimension. Invariably, it seems that if a change is made, one of the figures is overlooked and then two values remain on the drawing, causing needless confusion.

Composite surfaces

The illustrations so far given have been comparatively simple, as indeed are most of those met in practice. However, some pieces that must be manufactured have features that are quite involved and require many dimensions if they are to be defined exactly. The application of tolerances to many interrelated dimensions is likely to lead to violations of the rules of dimensioning and bring about discrepancies. For instance, a profile containing a number of angles and radii may assume quite widely divergent forms if each dimension is allowed to vary independently within workable limits.

A worth-while expedient is to dimension complicated forms without tolerances and specify an acceptable zone within which the profile may vary. Figure 112 shows an example of this method of controlling a profile in a manner that can be used directly in manufacturing.

A method of controlling gear teeth is a variation of the foregoing expedient. For instance, a spur gear may have errors in runout, tooth spacing, tooth thickness, involute form, etc. To keep all the errors so small that their sum would not hinder the gear's meshing would be costly. Each form of error has limits necessary to insure proper action and keep down noise, but if all should be large in any set of gears, the gears would probably not mesh freely. The actual expedient is to specify how a gear must run with a master. At a definite center distance, the backlash allowed between the gear and master may be specified. The stated amount of backlash must not be exceeded in any position of engagement. This is, of course, a check against the accumulation of the individual errors, and it is also commonly used for helical and bevel gears.

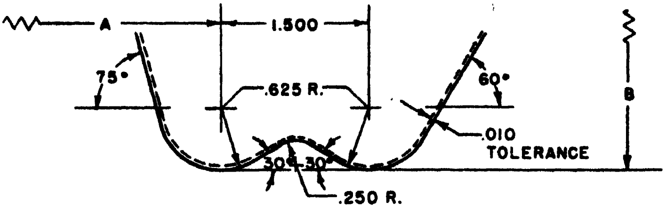


Fig. 112. A method of dimensioning a profile.

DIMENSIONING OF TOOL DRAWINGS

Dimensioning to suit the system of toolmaking

As explained in Chap. 6 in reference to estimating elapsed time for toolmaking, there are two distinct systems of toolmaking. By one system, practically all the work of construction of a single tool (jig, fixture, die, or gage) is done by one toolmaker or small group. The second system employs specialists who do certain types of work, such as milling, drilling, and boring, on all tool details. These specialists are usually not aware of the specific purposes of the details that they make. The various details of a tool go upon completion to a toolmaker who fits and assembles them.

Quite obviously the second system is akin to production, and tool drawings for it should satisfy the conventions and approach the completeness found desirable for production component drawings. Tolerances are usually specified for all but atmospheric dimensions.

For the first system, skilled toolmakers are essential, and much can safely be left to their discretion. Best results can often be achieved by leaving decisions as to tools and methods to be used in fabrication of the jig, fixture, die, or gage to the judgment of the toolmaker, where there is any opportunity to do so. For instance, tolerances are not customarily placed on the mating dimensions of a plug, press-fitted into a hole. The toolmaker can be depended upon to select the most suitable reamer available for the hole size and then to turn or grind the plug to an appropriate size within very close limits.

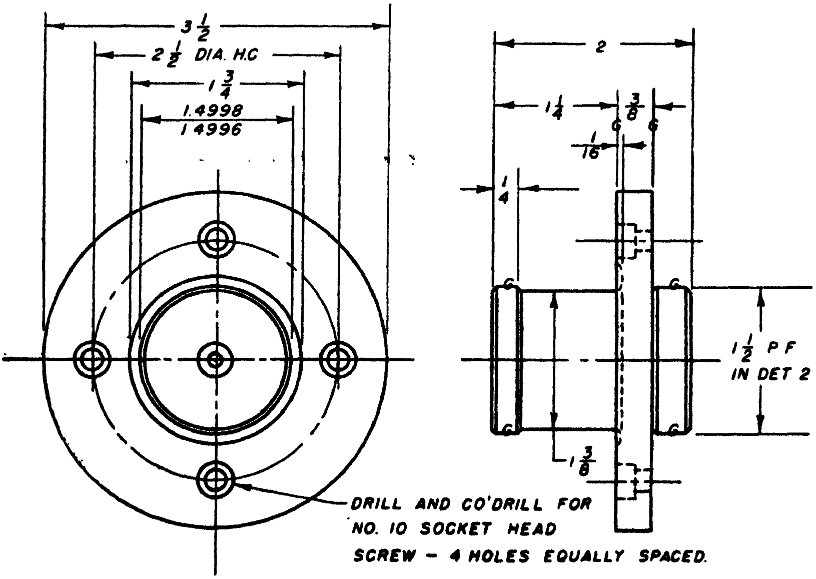
Where tolerances are necessary

Interchangeability between the details of many tools is seldom of any particular advantage. Details for replacement must usually be made individually and can, therefore, be fitted just as well as not. There are, of course, exceptions to this rule. Interchangeability is evidently a necessity in the case of a commercial universal jig.

Whatever the system by which tools are made, tolerances on the functional dimensions of tools must be specified if there is to be assurance that the tool will serve as planned. For instance, the diameter of an arbor on which a part must fit should have a specified tolerance. Also, the tolerance on the distance between a locating surface and the axis of a reamer bushing hole would normally be necessary to indicate the care necessary in jig boring the hole.

Some differences in practice in carrying out these principles are found in every plant. Figure 113 is given as one form of tool dimensioning to illustrate a drawing form intended to guide a skilled toolmaker. The top of the plug, over which the workpiece fits, is dimensioned with limits, but the bottom plug, which is to be pressed into the fixture body, has merely the nominal diameter specified with the note that it is a press fit into Detail 2. The clearance holes for the 10–24 NC socket head screws are merely stated as such. The toolmaker will probably have standard sets of tools for such holes, arranged for various sizes of screws. The geometric considerations are pointed out, and the toolmaker normally can be depended upon to exercise care in bringing the important geometrical relationships as close as possible.

Tolerances and relationships on tool drawings should not be specified more closely than necessary for to do so increases the cost of fabrication needlessly. For instance, it is evident that the location of a drill bushing for a hole that is located with a tolerance of 0.020 in. in the workpiece is not as important as that for a hole which must be located within 0.002 in. Even so, there are often practical limitations in the results that can be achieved by highly skilled tool-



DRILL AND CO'DRILL FOR NO. 10 SOCKET HEAD SCREW – 4 HOLES EQUALLY SPACED.

"G" SURFACES CONCENTRIC, SQUARE, AND PARALLEL AS APPLICABLE

① LOCATING PLUG – 1 REQ'D.
M. S. – CARB., HDN., & GRIND.

Fig. 113. A fixture detail. This illustrates one form of tool dimensioning.

makers—in jig boring, for example, and they must be taken into account in fixing tolerances upon tool dimensions. Some of the effects of tool tolerances upon production tolerances will be discussed in Chap. 14.

SUMMARY

An understanding of the principles of dimensioning is important to the tool engineer because dimensions are the principal media by which specifications are brought to him and passed on by him to others.

Tolerance is an important part of any dimension. For writing tolerances there are three principal forms:

1. The bilateral form that expresses the permissible variation in two directions from a stated dimension.
2. The unilateral form, applied in one direction.
3. Limits for specifying the extremes of a dimension.

Each form has certain appropriate areas of usage. In any case the desirable form may be determined by either (a) conditions of design or (b) the characteristics of the operation or process to do the job.

Tolerance forms may be used to carry out certain systems of design, such as:

1. Standard hole practice.
2. Standard shaft practice.
3. Maximum hole practice.

The proper amount of tolerance for any dimension depends upon:

1. Functional requirements.
2. The cost of production.

The best compromise must be sought between the first factor, which calls for a close tolerance, and the second, which urges a loose tolerance.

When functional requirements dictate very close tolerances, resort may be made to selective assembly. For that method of assembly, parts are made with comparatively wide tolerances, sorted to finer gradations, and assembled from groups.

For most applications, a few classes and grades of fit suffice.

Experience has shown the applications to which the standard classes are best suited. Thus tolerances may be applied readily by choosing them from the appropriate class for a particular situation.

To avoid confusion and misunderstanding in dimensions the following rules have been found helpful:

1. Locate a point by only one dimension in any one direction.
2. Dimension between points, lines, or planes which are naturally related to each other.
3. Provide dimensions in three co-ordinate directions to conform with functional needs.
4. Make the first or leading figure of a dimension the one which specifies what would be desirable if the distance could be held to an exact size.
5. Give no more than one dimension between any two points.

There are three kinds of surfaces on a part of a machine or mechanism. They are:

1. Functional surfaces, which make contact with surfaces of other parts.
2. Clearance surfaces, which have no contact with, but come close to, surfaces of other parts.
3. Atmospheric surfaces, which have no relationship to other parts.

The functional features of a part are most faithfully expressed by dimensions that connect its functional and clearance surface to its locating surfaces. Likewise, the functional features can be realized most naturally by using the surfaces that locate the part in service to locate it for finishing the other surfaces when it is made. These surfaces, which are most desirable for location, are known as the *critical surfaces* in manufacturing.

The plan followed in a toolroom may determine the way in which tool drawings are dimensioned. Where the tool work is divided among specialists, dimensioning like that for production drawings is appropriate; where skilled toolmakers carry through their jobs to completion, much may be left to their discretion. In either case, though, functional dimensions should be fully specified with tolerances on tool drawings.

QUESTIONS

1. Why is dimensioning important to the tool engineer?

2. What penalties may result from improper dimensioning?

3. Define: (a) tolerance, (b) allowance, (c) limits, (d) standard size.

4. How are tolerances written: (a) in the bilateral form? (b) in the unilateral form? (c) in the limiting dimension form?

5. What are advantages and disadvantages of the bilateral form of writing tolerances? Where is this form applicable?

6. What are advantages of the unilateral form of writing tolerances? Where is this form applicable?

7. Under what circumstances are limiting dimensions advantageous?

8. What conditions of design may point out certain tolerance forms as preferable?

9. Cite where process characteristics make one or another tolerance form desirable.

10. Describe: (a) standard hole practice, (b) standard shaft practice, (c) maximum hole practice. What benefits are attributable to each? What does each require in the way of tolerances?

11. What two considerations must be taken into account in fixing a tolerance?

12. What factors enter in fixing the allowance and tolerance of a running fit? What factors enter in fixing the allowance and tolerance of a press fit?

13. What is selective assembly? Why is it used?

14. Describe the eight classes of fit offered by the A.S.A. standards.

15. Give five important rules for good dimensioning practice.

16. Why should a point be located by only one dimension in any one line?

17. How should a taper be dimensioned? Give an example of an improperly dimensioned taper. What is the result?

18. Why should dimensions appear between related surfaces?

19. What is a datum plane?

20. Distinguish between functional surfaces, clearance surfaces, and atmospheric surfaces.

21. What are the most desirable surfaces to be used for datum or reference surfaces?

22. To what surfaces should functional and clearance surfaces be dimensioned?

23. What are critical surfaces? What relation is desirable between them and functional locating surfaces?

24. Why should the most desirable size be specified as the size of a dimension?

25. Why should only one dimension be given between any two points?

26. How may composite surfaces be dimensioned to avoid excess accumulations?

27. How does the way of making tools affect the method of dimensioning tool drawings?

28. For what dimensions on a tool drawing should tolerances always be given?

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10 DETERMINATION OF THE REQUIREMENTS AND CONDITIONS OF A PROCESS

The first step of process and tool planning

As outlined in Chap. 8, the first step of planning does not only consist of finding out what is to be done, but also of scrutinizing the adequacy of specifications, determining the nature of raw materials, the quantity of production, and the significance of specifications. These are the considerations that will be taken up in this chapter.

The specifications of a job tell what is to be done. Consideration will be given to the forms in which specifications are received and the immediate uses made of them.

A competent tool engineer is not expected to accept specifications blindly. As has been said before, he is often in the best position to evaluate requirements from a manufacturing standpoint. Attention will be given to the ways in which he can do that.

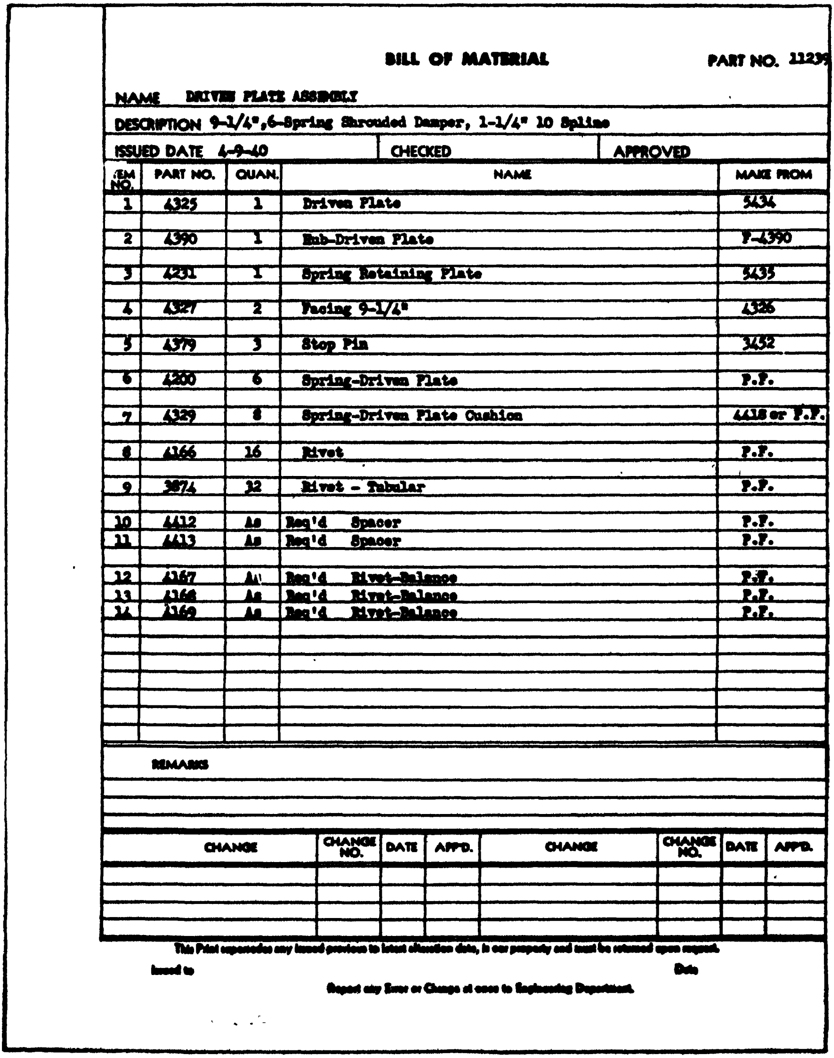
The raw materials desired or available and the quantity of production are among the most important conditions affecting a process. The significance of these items will be discussed.

Some specifications are more exacting than others. What makes them so and how they may be discerned will be studied.

TO FIND OUT WHAT IS TO BE DONE

How specifications are received

It is axiomatic that a statement of the requirements of a problem must precede its solution. Thus, before a process can be planned, it must be determined what the process is to accomplish. This is found first in a drawing of the part to be made. Assembly drawings, showing the functional positions of the parts, supplement most part drawings. Prints of the drawings are furnished with the manufacturing order, which specifies the conditions for the job. A bill of material, of which a sample is shown in Fig. 114, is almost always available for an assembly drawing. In addition, other helpful supplements may be available, like standard specification sheets, samples, or experimental models.



BILL OF MATERIAL PART NO. 11239

NAME DRIVEN PLATE ASSEMBLY

DESCRIPTION 9-1/4",6-Spring Shrouded Damper, 1-1/4" 10 Spline

ISSUED DATE 4-9-40	CHECKED	APPROVED

ITEM NO.	PART NO.	QUAN.	NAME	MAKE FROM
1	4325	1	Driven Plate	5434
2	4390	1	Hub-Driven Plate	F-4390
3	4231	1	Spring Retaining Plate	5435
4	4327	2	Facing 9-1/4"	4326
5	4379	3	Stop Pin	3452
6	4200	6	Spring-Driven Plate	P.F.
7	4329	8	Spring-Driven Plate Cushion	4418 or P.F.
8	4166	16	Rivet	P.F.
9	3874	32	Rivet - Tubular	P.F.
10	4412	As	Req'd Spacer	P.F.
11	4413	As	Req'd Spacer	P.F.
12	4167	As	Req'd Rivet-Balance	P.F.
13	4168	As	Req'd Rivet-Balance	P.F.
14	4169	As	Req'd Rivet-Balance	P.F.

REMARKS

CHANGE	CHANGE NO.	DATE	APP'D.	CHANGE	CHANGE NO.	DATE	APP'D.

This Print supersedes any issued previous to latest alteration date, is our property and must be returned upon request.

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Report any Error or Change at once to Engineering Department.

Fig. 114. A typical bill of material. (Courtesy Borg and Beck Co.)

Figure 3 shows how the specifications pass from the product engineer to the factory manager to the tool engineer, and later steps that they take.

What the specifications include

For a manufactured article, the requirements may include:

1. The surfaces to be finished, whether external or internal, and their geometric forms, such as:
    a. External diameters,
    b. Holes,
    c. Plane surfaces,
    d. Special forms, like involute surfaces.
2. The degree of finish for each surface.
3. The dimensions between surfaces.
    a. Between finished plane surfaces and rough and finished surfaces.
    b. Diameters of cylindrical surfaces, external and internal.
    c. Lengths of outside diameters and depths of holes.
    d. Between axes and planes or from axis to axis.
4. Geometric relationships, such as
    a. Concentricity,
    b. Parallelism,
    c. Squareness,
    d. Angularity.
5. The allowable limits of each dimension and relationship.
6. Physical properties of the material, such as
    a. Hardness.
    b. Toughness.
7. Surface treatment.
    a. Plating.
    b. Painting.
8. Refinements.
    a. Burring.
    b. Chamfering or countersinking.
    c. Blending of surfaces.
    d. Tapping or threading.

From the data furnished, the engineer should compile at the start a mental or written list of every requirement, checking off each from the print as it is noted. By recognizing each essential item he can be sure of a comprehensive understanding of what must be accomplished.

INVESTIGATION OF SPECIFICATIONS

Clarification of obscure requirements

It is important that all statements of requirements be explicit. Any information not covered by standard practice should be conveyed on the part print in such a way as to leave no room for a misunderstanding. Dimensions without tolerances, notes reading "Break Edges," and surfaces designating merely the mark "f" are examples of deficient designations that too often lead to misunderstandings. If information is lacking, the process engineer must secure it from the product engineer and insist that it be placed on the drawing. The alternative is to "second guess" the designer with the resultant risk of inadequacy and error.

Improvement of design

The general nature of a process is usually inherent in the design of an article. A design calling for grey iron implies that it will be cast and then machined on those surfaces where greater than casting accuracy is required. A bevel gear can be expected to be processed somewhat differently from a spur or helical gear. Thus, when the process engineer has ascertained the requirements of the design of a part, he has determined, in a large measure, the general aspects of the process he will choose. His task is to find the most favorable variation of that process, from the standpoint of economy and expediency, that will meet the requirements. However, he must never assume that all decisions that have been made are conclusive but should be always alert to constructive possibilities and strive to suggest improvements in design. Often the production engineer can save a great deal in tooling and manufacturing costs by suggesting changes in product design to conform to basic principles and, what is more important in many cases, can bring about lower costs by pointing out the desirable design for that type of process implied by the requirements. As a rule, to which there are always exceptions, the product engineer is primarily interested in the functional aspects of a design and only secondarily concerned with processes.

The process or tool engineer has, of necessity, production as his main consideration and is in a better position to bring a more specialized and intensive knowledge of that field to a problem. To broaden his outlook, however, it is always desirable for him to cultivate some understanding of the nature of the product engineer's problems.

Many examples can be cited to illustrate design improvements affected by adroit process engineering. Two are given at this time. The gear cluster for an aircraft engine was originally designed in three parts as shown in Fig. 115A. A large gear and a small one were assembled on a splined core, which was staked over on one end to hold the assembly together. Since the two gears had to be hardened and finished to close limits and a space of only $\frac{3}{16}$ in. was allowable between the gears, the designer was of the opinion that the components must be processed separately to provide adequate clearance for finishing them by conventional methods. The large gear presents no problem, but the smaller one is too close and too far below the larger one to allow easy access of the usual types of rotating finishing cutters or grinding wheels. Considerable difficulty was introduced into the job by the necessity of limiting the errors in each part to amounts that, added together in the assembly, would

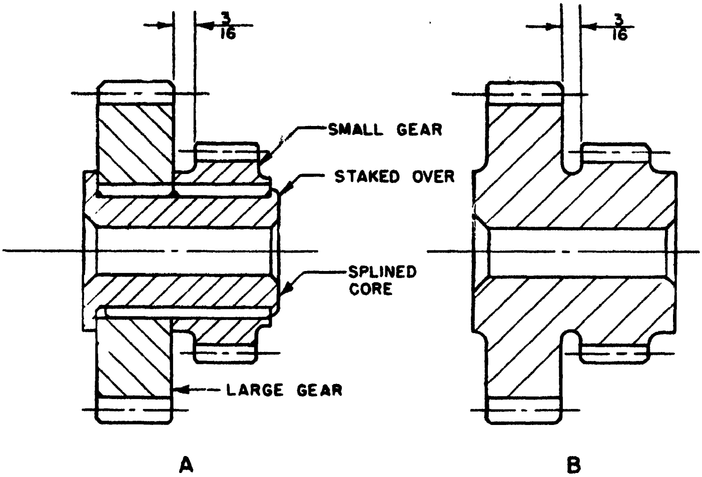


Fig. 115. A cluster gear. (A) As originally assembled from three parts for an aircraft engine. (B) Refinement in process brought about simplification to one part at a lower cost.

be within the tolerances of the finished unit. To improve the situation, the process engineer together with equipment manufacturers devised a method together with the necessary tools for shaving the small gear in its location near the larger one and made possible the design sketched in Fig. 115B. The one piece construction obviously is much more economical to manufacture.

Figure 116A represents the original design of an aircraft oxygen tank bracket, which evidently is costly because of the number of parts and assembly operations required. Figure 116B is a simplified design suggested by production experts, but rejected by the product engineer because it was not properly stressed. Figure 116C is a design offered to incorporate the desirable characteristics of the first two designs, but its turned-in lips made fabrication difficult. Figure 116D shows the design of the bracket finally adopted.

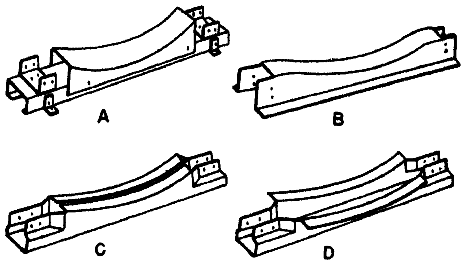


Fig. 116. Part design simplifies production. (Courtesy of *Production Engineering and Management.*)

Design changes to improve operations

Frequently changes in or additions to a workpiece, even though minor, may be helpful to producing it. Changes should be made at the start, because later, especially in production, they are more expensive. All the possible refinements that aid production are too many to list. However, the following outline gives an idea of the kinds of changes that are common and is offered as a guide of what the process and tool engineer should bear in mind when looking for improvements.

Typical alterations are:

1. Additions to the workpiece in the form of pads, ribs, fins, lugs, reliefs, etc., to:

a. Control warpage in heat treatment or founding. Figures 117 and 118 show two precautions for castings.

b. Control workpiece deflection under cutting and clamping forces. For instance, a thin flange that may be difficult to support under cutting forces may be reinforced by ribs.

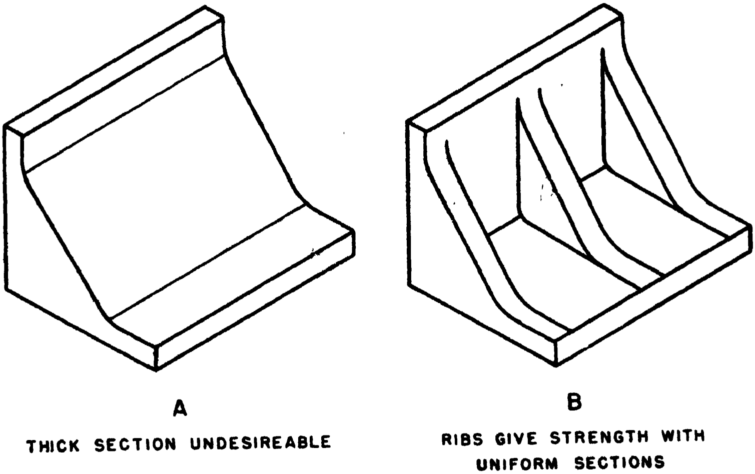

A
THICK SECTION UNDESIREABLE
B
RIBS GIVE STRENGTH WITH UNIFORM SECTIONS

Fig. 117. A design to improve a casting. The bracket at (A) with the heavy fillet has a thick section that can be expected to cool more slowly than the thinner adjacent walls and set up stresses and resultant deformations. Gas pockets and a spongy formation are more likely within the thick section. The bracket at (B) has the walls reinforced by ribs, which provide thinner sections and ample strength.

c. Provide strength to withstand cutting action that might break or damage the part. An example is furnished by the countersink in Fig. 119 to get away from breakout from tapping.

d. Aid in holding the workpiece. Chucking rings and bosses

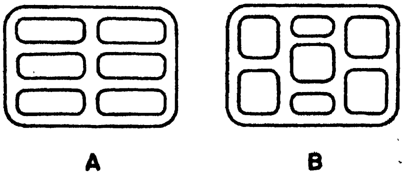


Fig. 118. A design to improve a casting. The staggered ribs, at (B), cause less distortion than the regularly spaced ribs at (A).

are often added for this purpose. The worm gear of Fig. 120A required two chuckings (2 operations) for machining. The chucking boss shown added in Fig. 120B made it possible to machine the gear in one chucking. At the end of the single operation, the piece is cut from the chucking boss by the cut-off tool, *x*, which also finishes the hub face.

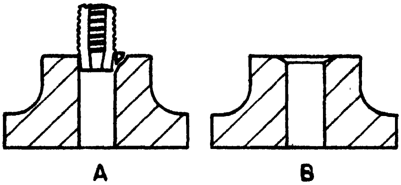


Fig. 119. Design to withstand cutting action. If a cored hole is to be tapped, particularly in brittle materials, a sharp edge may break out. A countersink to overcome breakage is preferred.

e. Aid in driving the workpiece. A slot or projection may be added to a piece for contact with a driving pin, if the piece is to be turned on a lathe. The small crankshaft, shown in Fig. 121, has lugs on the end so that it can be turned between centers for machining the crank pin as well as the main journal. In the end, the lugs are cut off to finish the part.

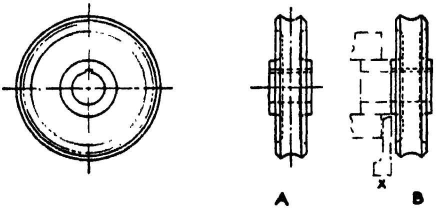


Fig. 120. A worm gear at (A) to which a chucking boss was added, at (B). (From Owens, *Introduction to Tool Engineering*, p. 60. Prentice-Hall, 1948.)

f. Aid in locating the workpiece. That is part of the function of the lugs on the crankshaft of Fig. 121. Foundry pads may be added to castings to serve as locators in the initial machining operations. The small cylinder block of Fig. 122 has pads for that purpose. These pads have no functional purpose.

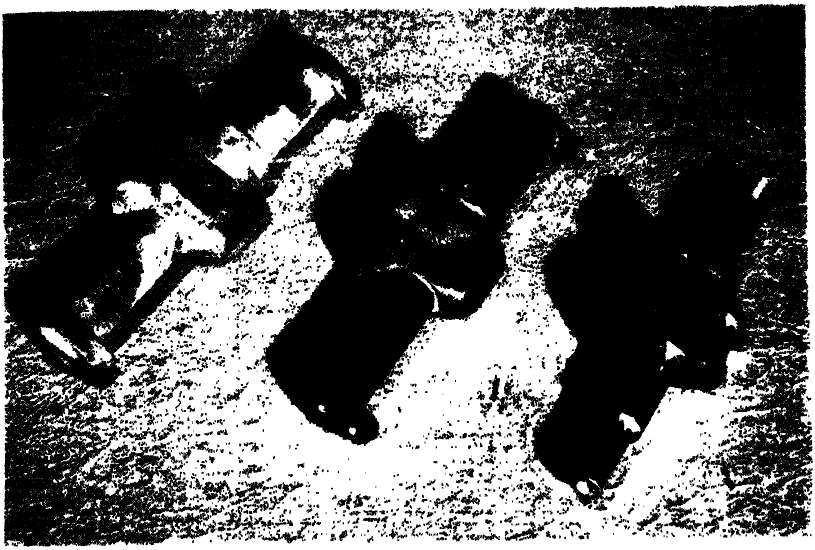


Fig. 121. An aid for driving and locating. The small crankshaft is cast with lugs on the ends, as shown on the left. Two center holes are put into each lug for driving and locating the piece for machining the main journals and the crank pin, as shown by the piece in the middle. When the crankshaft is finished, the lugs are turned off. A finished piece is on the right.

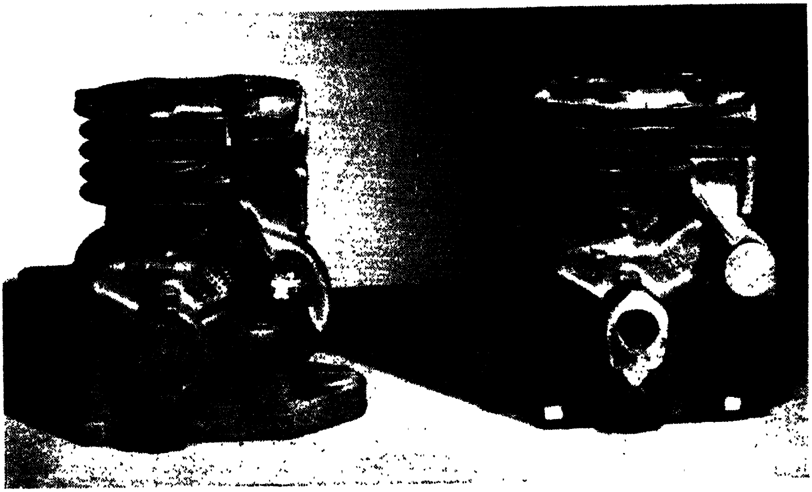


Fig. 122. Two views of a small cylinder block casting. The foundry pads from which location is taken for the initial machining operations are shown. The positions of these pads on some castings are checked in a fixture that registers the important outlines of the casting. The pads may be filed or cut to provide location within 0.010 in.

g. Prevent mutilation or marring of the workpiece. The gear of Fig. 123 would have burrs thrown into the spline when the end face is finished if it were not for the counterbore. When the piece of Fig. 124 was designed with a groove around the edge, a parting line across the face was necessary. The flash was difficult to remove

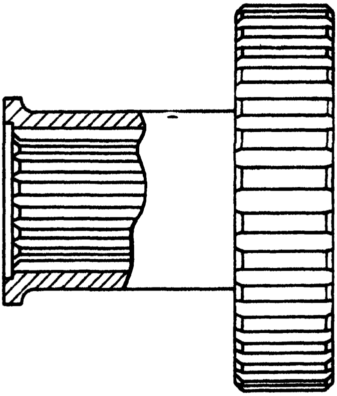


Fig. 123. A design to avoid mutilation. The shank end of this gear must be ground after heat treatment. A counterbore is provided in the end of the splined hole so that the grinding does not throw a burr into the spline, which would be difficult to remove.

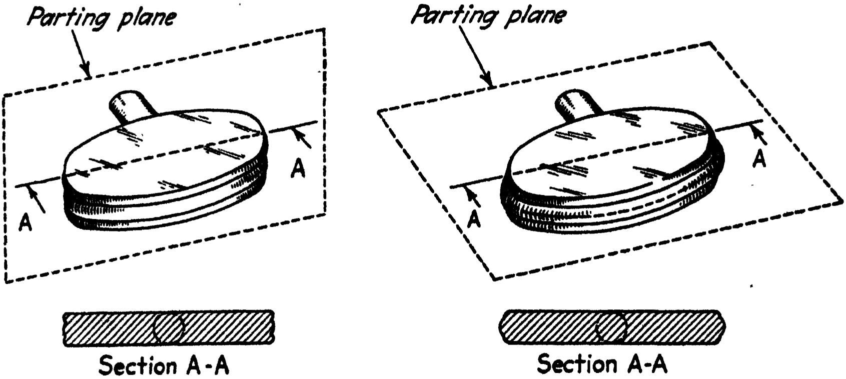


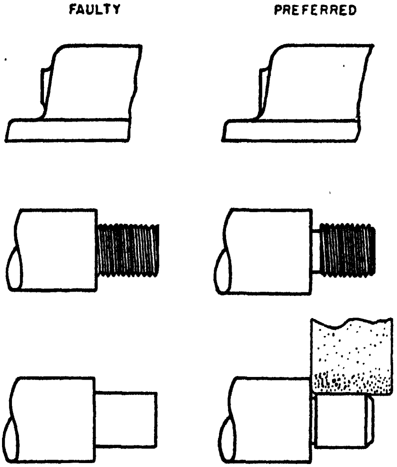
Fig. 124. A design to prevent mutilation. Grooves around the contour of this handle, as at left, require parting the die in a vertical plane, leaving flash where its removal is difficult and mutilates the workpiece. The design at right makes possible a horizontal parting with easier flash removal. (Courtesy New Jersey Zinc Co., New York.)

without marring the face. With a bead instead of a groove around the edge, the die could be parted at the bead from which flash could be removed without scratching the face.

h. Conform to characteristics of tools. Several examples are given in Fig. 125.

2. Changes in shape or size of the workpiece to reduce:

a. Tooling costs. Simple changes in die castings to reduce



EXPLANATION

The undercut below the boss, at left, calls for an extra core for casting. That may be avoided by extending the boss to the base, like at right.

The thread on the left is difficult to cut all the way to the shoulder, especially with a die which must have lead. A relief or neck at the shoulder and a chamfer on the end to help start the die, like at right, are desireable.

A sharp corner at a shoulder is hard to get with a grinding wheel which breaks down on the edge. A grinding relief, shown on the right, is good practice.

Fig. 125. Several examples of design to conform to characteristics of tools.

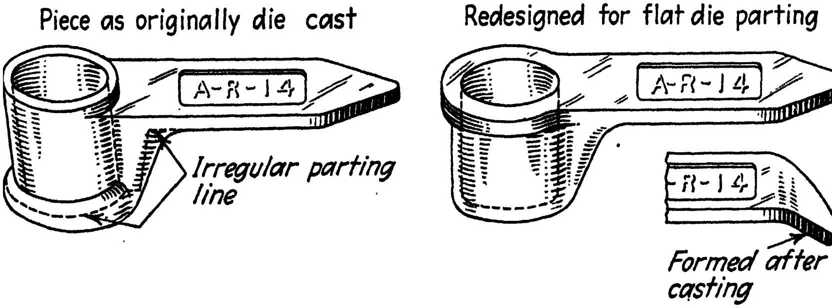


Fig. 126. A design to reduce tool costs. With a die casting designed as shown at left, an irregular parting face (in dashed lines) is required. Redesign, at right, permits a flat parting with lower cost for the die and for flash removal tools. (Courtesy New Jersey Zinc Co., New York.)

die costs are suggested in Figs. 126 and 127. Wherever possible, the use of standard sizes of tools is desirable, especially drills, reamers, and counterbores. They cost much less than special tools and can be used with standard bushings. Standard tools are also

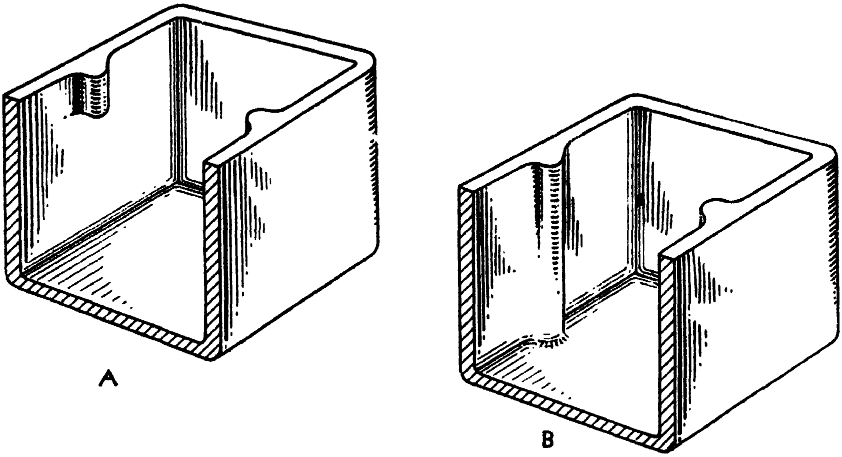


Fig. 127. A design to reduce tool costs. Internal lugs involving undercuts, as in *A*, require an expensive collapsible core or "knock outs." If the lug is extended, as in *B*, an undercut is avoided. (Courtesy New Jersey Zinc Co., New York.)

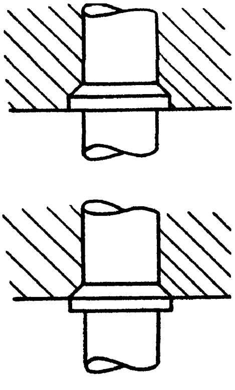


Fig. 128. A design for standard tools. A special combination countersinking and counterboring tool is necessary to make the hole for the construction at the top. For that at the bottom, only a standard countersink is needed.

more readily available. Special form tools are often justifiable where they are used to cut several surfaces at once, but even then their necessity may be obviated at times by a change in the shape of the part, as suggested for one case by Fig. 128.

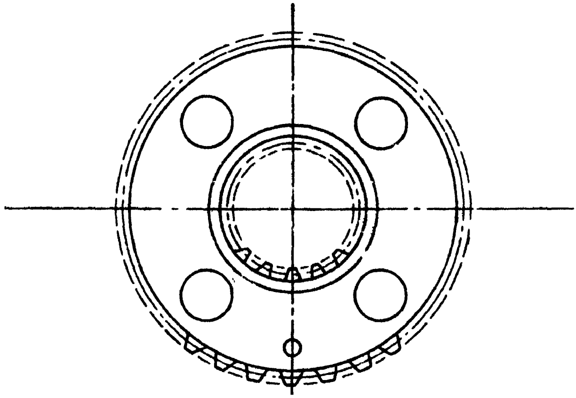
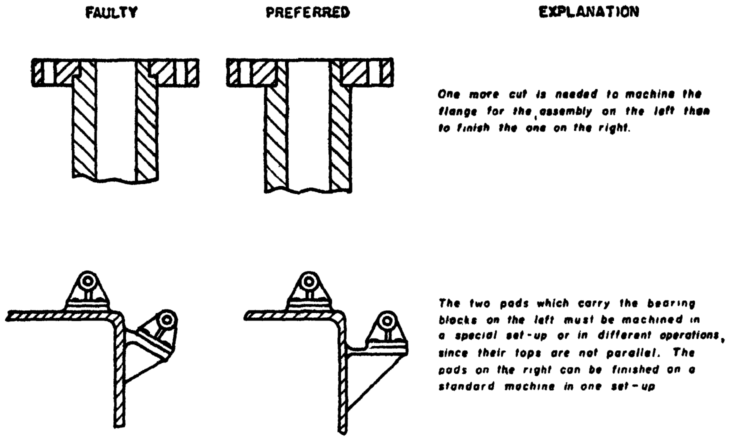


Fig. 129. Design for foolproofing. One tooth of the external gear must align with one tooth of the internal spline, in relation to the four large holes all of the same size, as indicated. Addition of the small foolproofing hole (which has no functional utility after the part is finished) for locating in the various fixtures and jigs provided means for maintaining the desired relationships.

b. Operator Skill. An example of foolproofing by a change in shape, consisting of the addition of a small hole, is shown in Fig. 129. The addition of dowel holes to make the location of a center line datum plane was suggested for the pieces of Fig. 110. Without some such means, machining of the parts to dimensions given from the center lines would be difficult.

c. The number of steps or operations to make a part. For instance, some surfaces may be economically ground from the rough if the rough size is decreased to leave a minimum of stock, thus eliminating machining operations. Two other examples of how manufacturing steps may be reduced are shown in Fig. 130. Lugs may be added to a part to facilitate assembly, as suggested by Fig. 131.

d. Material Costs. When the small hydraulic piston shown in Fig. 132 was made from bar stock, the waste material per piece amounted to 7.88 lb. Not only was most of that material saved by



One more cut is needed to machine the flange for the assembly on the left than to finish the one on the right.

The two pads which carry the bearing blocks on the left must be machined in a special set-up or in different operations, since their tops are not parallel. The pads on the right can be finished on a standard machine in one set-up

Fig. 130. Two examples of how machining steps may be reduced.

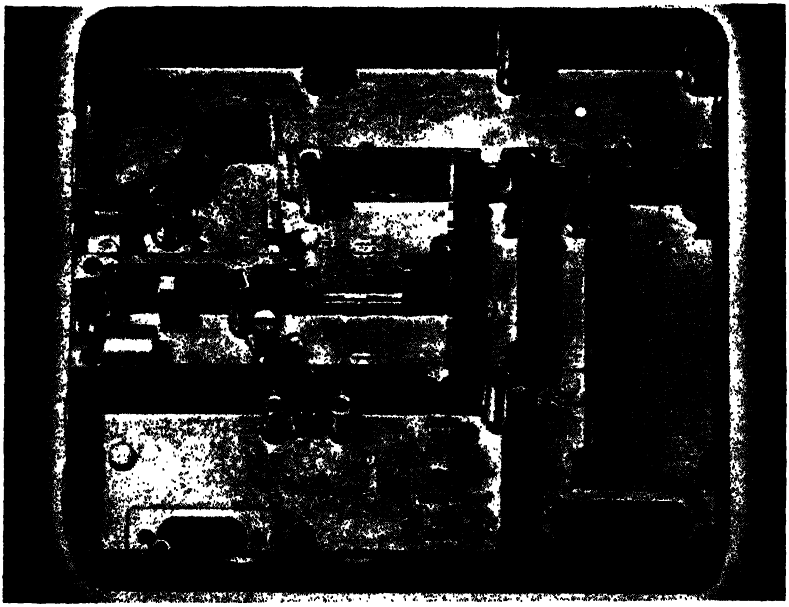


Fig. 131. A design to help assembly. This complex radio chassis is a die casting, which allows the inclusion of lugs and supports without which assembly operations would be greatly increased and economical manufacture unlikely. (Courtesy New Jersey Zinc Co., New York.)

brazing together pieces from two sizes of bar stock, but also more than 60 per cent of the machining time was eliminated.

Other savings such as storage, may be more important than the material alone. For instance, the single bracket, described in Fig. 133, in place of two others, makes it possible to reduce the

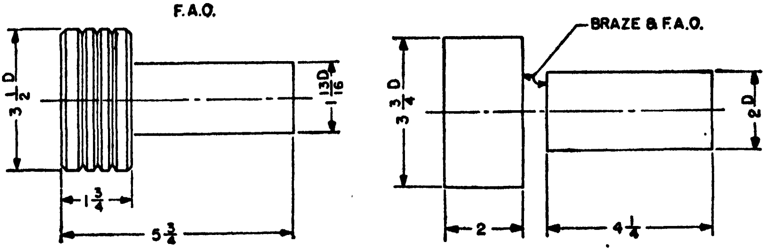


Fig. 132. A small hydraulic piston. (From Owens, *Introduction to Tool Engineering*, p. 72, Prentice-Hall, 1948.)

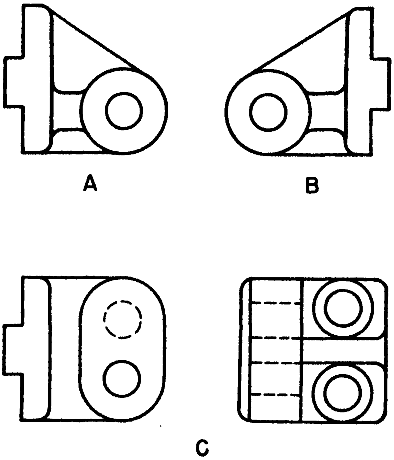


Fig. 133. A design to reduce the number of rough pieces. Instead of the right and left hand brackets, (A) and (B), requiring separate castings, brackets can be made from a single casting as at (C). The position of the hole in the arm is the only difference between the two brackets in their redesigned form. Besides the savings resulting from process simplification, there is the advantage of being able to make either bracket, whichever may be needed more, from the rough casting.

number of rough pieces that must be stored and simplifies processing.

The savings possible from the use of standard sizes and shapes of raw materials should not be overlooked. These include standard sizes of round, hexagon, and square bars, tubes, and sheets. Such standard items are usually cheaper, easier to stock, and less subject to obsolescence than special sizes and shapes.

DETERMINATION OF THE CONDITIONS OF A PROCESS

Material

A process involves a change in size, form, shape, or characteristics of material. Thus, determination of the nature of the raw material is always a prerequisite to planning the process. Much of the necessary information is usually supplied in the design of the article, but some may have to be ascertained from other sources. For instance, the part print may specify SAE 3120 steel for a shaft having a major diameter of 1⅝ in., but the process engineer must determine the diameter of the bar stock to be purchased on the bases of the amount of stock needed over the largest finished diameter and the commercial sizes available. For a gear, the process engineer may have to determine, from the standpoint of economy, whether to machine it from bar stock, tubing or forgings. Another part may be cut from extruded strip or die cast.

Quantity

The quantity to be made of any article is of paramount importance in the determination of the process to be used. That information is not normally available in the engineering specifications of the part, although often records supplying the information accompany the engineering release given to the process engineer. The decision as to the required output is one that management must make on the basis of market surveys. The resulting information can be expected from the management.

DETERMINATION OF EXACTING REQUIREMENTS

The selection of critical areas

Observation of the individual dimensions of an object is only a part of recognition. An understanding of their significance must follow. Especially those requirements that are exceptionally exacting must be discerned. They are the ones that must receive the most careful treatment during the process.

As was pointed out in Chap. 9, certain areas of a part carry out its functions. These areas have special features. If the functions are exacting, the dimensions between the functional areas must be held closely and the surfaces must be true geometrically. This was illustrated by the shaft of Fig. 111. It is suggested that the explanation in the text of that figure be reviewed at this time.

Even where the function of a part is not exacting, there are functional surfaces that stand out. For instance, a cast bracket may be adjustable and does not need close dimensions. Even so, certain locating and adjusting surfaces need to be finished. These surfaces are favored as compared with the surfaces left in the rough, even though no surfaces on the part are particularly exacting.

The functional areas are especially qualified because of their required purposes, positions, and truth as areas from which to locate, measure, or gage other areas of a workpiece. In that role they are called *critical areas*. Functional areas are designated by the product designer by the dimensions and qualifications given on the drawing of a part. From these the critical areas are chosen on the basis of their suitability for the process for making the part, because some functional areas make better critical areas than others. In addition, clearance surfaces often offer advantages as critical areas because of position, shape, or size.

General indicators of critical areas are:

1. The presence of base lines from which dimensions are taken in the three co-ordinate directions or radially. These lines usually coincide with surfaces of the workpiece.

As an example, a plate of steel has a number of holes perpendicular to the top, as shown in Fig. 134. The holes are located by coordinate dimensions (A_1, B_1, C_1, and A_2, B_2, C_2) with close limits from two edges of the plate. The edges, representing axes, merit special consideration and are the critical areas in this case.

2. Close tolerances on dimensions which may be measurements of distances between points or surfaces, conditions of roundness and straightness of cylindrical surfaces, or conditions of concentricity or squareness between surfaces.

As an example, the design of a piece machined from a casting calls for two holes perpendicular to a plane. One hole must be 1.000–1.001 in. in diameter and the other 0.7500–0.7505 in. in diameter. The distance between the hole centers is specified as 10.001–9.999 in The holes are likely critical areas of the part. They present a condition that demands close attention to machining and gaging. The holes also offer desirable means for location of the part while other surfaces are being machined.

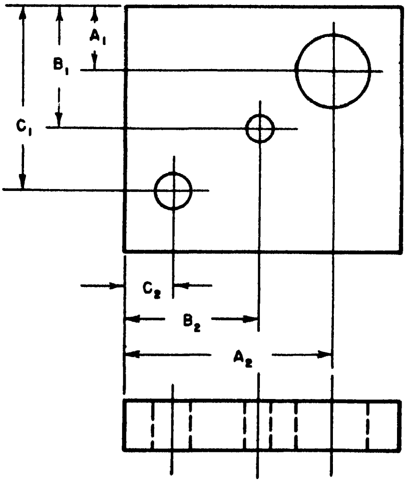


Fig. 134. Critical areas. The holes in the plate are located by dimensions with close limits from two edges, which are the critical surfaces of the piece. This is especially true if the diameters of the holes do not have close tolerances.

As another example, a cluster gear has two bearing surfaces at its ends, perpendicular to its axis, a distance of 7.5005–7.500 in. apart. These surfaces must be square with the axis of the gear cluster within 0.001 total indicator reading. Obviously, these conditions are indicative of critical areas.

3. Surface restrictions pertaining to finish or flatness. For instance, the finished surfaces on a casting, even though no close tolerances apply to the dimensions positioning the surfaces.

The indicators of critical areas may point to several surfaces of a workpiece. *A selection of the most pertinent critical areas* for a particular process must be made to determine which will provide the most advantages. Three tests which will help in this selection are:

A test for arithmetical superiority. If two surfaces have a relating dimension with close limits, both may be critical areas. However, if one is directly related dimensionally to other surfaces of importance, and the second is not, the first is the more important critical surface. In its role of locating surface, the first will present fewer difficulties in the way of limit stacks and necessary tightening of tolerances. Generally, those areas are the most critical which contribute most to minimizing limit stacks and tolerance accumulations.

A test for geometrical superiority. A surface less subject to run-out variations is more desirable as a critical surface for subsequent locations.

In general, preference should be given to critical areas that will provide locating points the greatest distance apart. For instance, two holes in a piece 10 in. apart are better locators than two holes a shorter distance apart, other conditions being equal. Also, a large surface is a more stable locating area than a small surface.

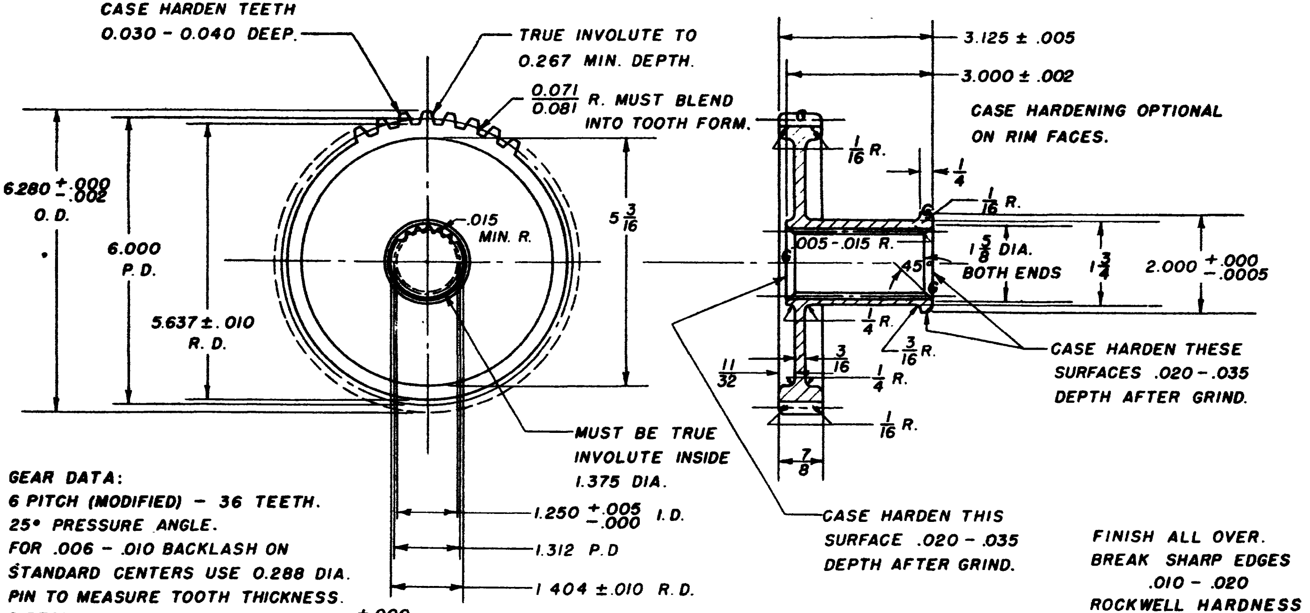
A test for mechanical superiority. A surface having a minimum tendency towards deflection and mutilation is a more desirable locator.

EXAMPLE 18: An analysis of the critical areas of the gear of Fig. 135 will serve to illustrate the evaluation and selection of critical areas.

The 3.000 ± 0.002 dimension between the ends of the hub and the requirements that those surfaces be square with the spline within 0.002 total indicator readings indicate that those surfaces are critical. Also, both surfaces must be finish-ground after heat treatment. The face of the long end of the hub possesses special arithmetical superiority in being a terminal surface for both length dimensions with close tolerances (the 3.125 ± 0.005 and the 3.000 ± 0.002 dimensions), but both hub faces are comparatively weak geometrically in having a small diameter in comparison with the over-all diameter of the gear. They are well placed to reinforce the spline while it is being cut.

The rim face on the short hub side of the gear has a close dimensional relationship with the other critical faces (although not the closest), but possesses the exceptional advantages of having a broad locating base, of providing a desirable mechanical support for the gear teeth, and of being near the critical face of the short hub, the outside diameter, and the teeth.

Because of the accuracy required of the gear teeth, the wide spread that they offer between locating points, and their necessary concentricity in relation to the spline, the teeth may be taken as critical areas. However ac-


CASE HARDEN TEETH 0.030 - 0.040 DEEP.
TRUE INVOLUTE TO 0.267 MIN. DEPTH.
$\frac{0.071}{0.081}$ R. MUST BLEND INTO TOOTH FORM.
$6.280 \begin{smallmatrix}+.000\\-.002\end{smallmatrix}$ O. D.
6.000 P. D.
5.637 ± .010 R. D.
.015 MIN. R.
$5\frac{3}{16}$
MUST BE TRUE INVOLUTE INSIDE 1.375 DIA.
$1.250 \begin{smallmatrix}+.005\\-.000\end{smallmatrix}$ I. D.
1.312 P. D
1 404 ± .010 R. D.
3.125 ± .005
3.000 ± .002
CASE HARDENING OPTIONAL ON RIM FACES.
$\frac{1}{16}$ R.
$\frac{1}{4}$
$\frac{1}{16}$ R.
.005 - .015 R.
$1\frac{5}{8}$ DIA. BOTH ENDS
45°
$1\frac{3}{4}$
$2.000 \begin{smallmatrix}+.000\\-.0005\end{smallmatrix}$
$\frac{1}{4}$ R.
$\frac{3}{16}$ R.
$\frac{3}{16}$
$\frac{11}{32}$
$\frac{1}{4}$ R.
$\frac{1}{16}$ R.
$\frac{7}{8}$
CASE HARDEN THESE SURFACES .020 - .035 DEPTH AFTER GRIND.
CASE HARDEN THIS SURFACE .020 - .035 DEPTH AFTER GRIND.

GEAR DATA:
6 PITCH (MODIFIED) - 36 TEETH.
25° PRESSURE ANGLE.
FOR .006 - .010 BACKLASH ON STANDARD CENTERS USE 0.288 DIA. PIN TO MEASURE TOOTH THICKNESS.
DISTANCE ACROSS 2 PINS = $6.3972 \begin{smallmatrix}+.000\\-.0039\end{smallmatrix}$
TOOTH THICKNESS AT P. L. = $0.2587 \begin{smallmatrix}+.000\\-.002\end{smallmatrix}$ (CHORD)
CORRECTED ADDENDUM = 0.1428.

GROUND SURFACES AND PITCH LINE OF GEAR MUST BE SQUARE AND CONCENTRIC WITH P. L. OF SPLINE WITHIN 0.002 TOTAL INDICATOR READING.

INVOLUTE SPLINE DATA ·
16/32 PITCH - 21 TEETH - 20° P. A.
WIDTH OF SPACE AT P. L. = $0.0981 \begin{smallmatrix}+.001\\-.000\end{smallmatrix}$ (CHORD).
CUT TO GAGE.

FINISH ALL OVER.
BREAK SHARP EDGES .010 - .020
ROCKWELL HARDNESS
CORE 30 C MIN.
CASE 58 C MIN.

MATERIAL:
S. A. E. 3120 STEEL.

UNSPECIFIED TOLERANCES ±.010

Fig. 135. A typical gear for an aircraft engine.

curate locating devices for involute profiles are expensive and not entirely desirable if they can be avoided, although necessary at times.

The outside diameter of the gear is to be held closely to $6.280\,^{+0.000}_{-0.002}$ in., will have to be ground after heat treatment, offers widely spaced locating points, and must be concentric with the spline axis. The periphery, therefore, has a claim to being considered as a critical area. It has the disadvantage of being inaccessible as a locator when the gear teeth are being cut or finished, an important part of the process.

The $2.000\,^{+0.000}_{-0.0005}$-in. diameter must be ground and must be held concentric within .002 total indicator reading with the spline. Those indicators point to its being a critical area. However, it is so short, ¼ in., that it should be avoided, if possible, or used as an auxiliary locating surface in conjunction with other surfaces.

The internal spline offers the most advantages as a radial locator. Its dimensional limits are close (tooth thickness $0.0981\,^{+0.001}_{-0.000}$ at the pitch line); its length of almost 3 in. gives it a satisfactory bearing area; it is related by concentricity requirements with the periphery and teeth of the gear, the 2-in. diameter, and, most important of all, to the surfaces at the ends of the hub. On the other hand, spline teeth are not good locating surfaces because of their special form and the expense of making and maintaining locating devices to suit them. Also, since the spline is not hardened, as the ends of the hub are, it may be preferable to delay cutting the teeth until very late in the process and thus the spline will not be available as a locator during most of the operations. An expedient that is frequently made use of is to machine the internal diameter of the spline to a closer tolerance than required in the finished part and thus make the hole serve as a substitute critical area for the spline. The hole possesses most of the qualifications of the spline and is lacking only in that in the final analysis it in itself does not have a direct part in the function of the gear.

Problem 41. Point out the relative merits of the surfaces of the bracket of Fig. 5 as critical areas.

Problem 42. What are the critical areas of the bearing bracket of Fig. 136? Of the bearing cap?

Problem 43. What are the critical areas of the valve cap of Fig. 137?

Problem 44. Point out the critical areas indicated in Fig. 138 and evaluate their relative merits.

Problem 45. The dimensional surfaces of Fig. 139 are to be finished from a forging. Other surfaces are left rough. Discuss the relative merits of the critical surfaces.

SUMMARY

The first step of process and tool planning is to find out what is to be done. That includes determining that the specifications are

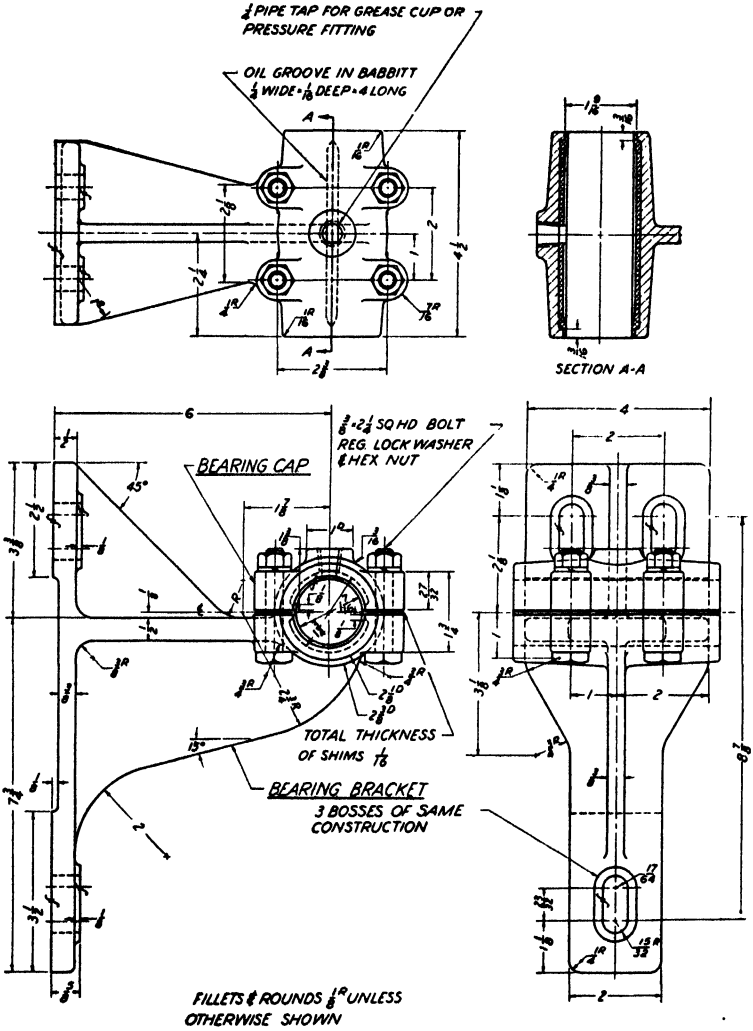

1/4 PIPE TAP FOR GREASE CUP OR PRESSURE FITTING
OIL GROOVE IN BABBITT 1/4 WIDE × 1/16 DEEP × 4 LONG
A
A
1/16 R
1/4 R
1/16 R
7/16 R
2 1/8
2 1/4
2
1
4 1/2
2 3/8
1 9/16
3/16
3/16
SECTION A-A
6
3/8 × 2 1/4 SQ HD BOLT REG. LOCK WASHER & HEX NUT
BEARING CAP
45°
1 7/8
1 R
1 3/8
3/16
27/32
1 3/4
R
℄
2 1/2
3 7/8
1/2
3/8 R
2 1/8 D
2 3/8 D
TOTAL THICKNESS OF SHIMS 1/16
15°
BEARING BRACKET
3 BOSSES OF SAME CONSTRUCTION
2
7 3/4
3 1/2
5/8
4
2
1/4 R
1 1/8
2 1/8
1
3 1/8
3/8 R
1
2
8 7/8
17/64
15/32 R
1 1/8
1/4 R
2
FILLETS & ROUNDS 1/8 R UNLESS OTHERWISE SHOWN

Fig. 136. A bearing bracket assembly. (From Luzadder, *Fundamentals of Engineering Drawing*, p. 327, Prentice-Hall, 1946.)

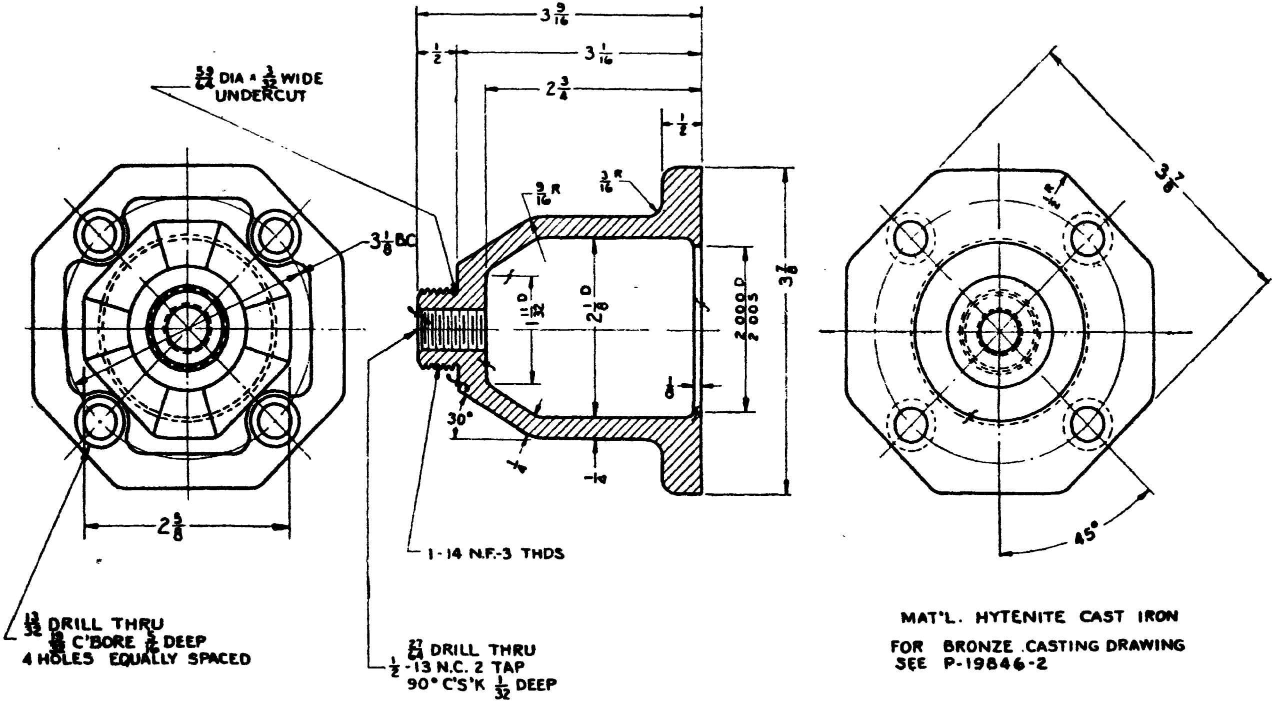


Fig. 137. A valve cap. (From Owen, *Introduction to Tool Engineering*, p. 38, Prentice-Hall, 1948.)

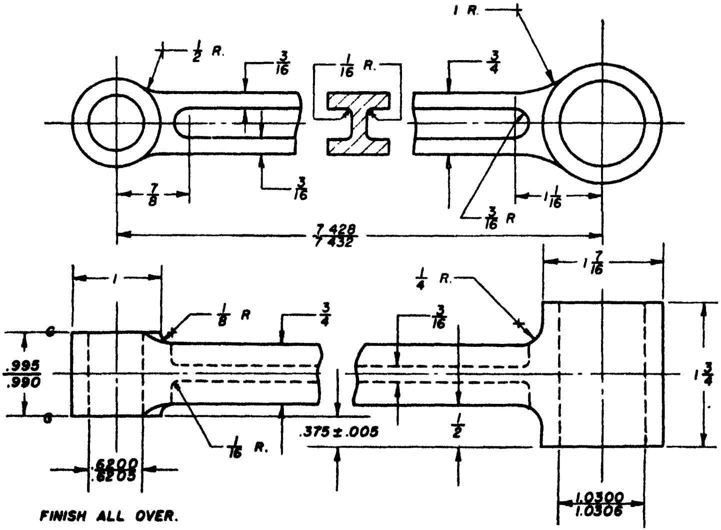
adequate, the raw materials to be used, the quantity to be produced, and what requirements are exacting.

Specifications for a job are mainly found in the part prints. They may be supplemented by assembly prints, bills of materials, specification sheets, samples, and models. The necessary information includes specifications of:

1. The surfaces to be finished.
2. Finishes required.
3. Dimensions.
4. Geometric relations.
5. Tolerances.
6. Material properties.
7. Surface treatment.
8. Refinements desired.

For specifications to be adequate they must be explicit and complete.

The design of an article to a large extent dictates the process for making it. The process and tool engineer is in a good position



FINISH ALL OVER.
MATERIAL: S. A. E. 3140 STEEL.
MAKE FROM FORGING HEAT TREATED TO 27–32 ROCKWELL "C" HARDNESS.

Fig. 138. Articulated rod.

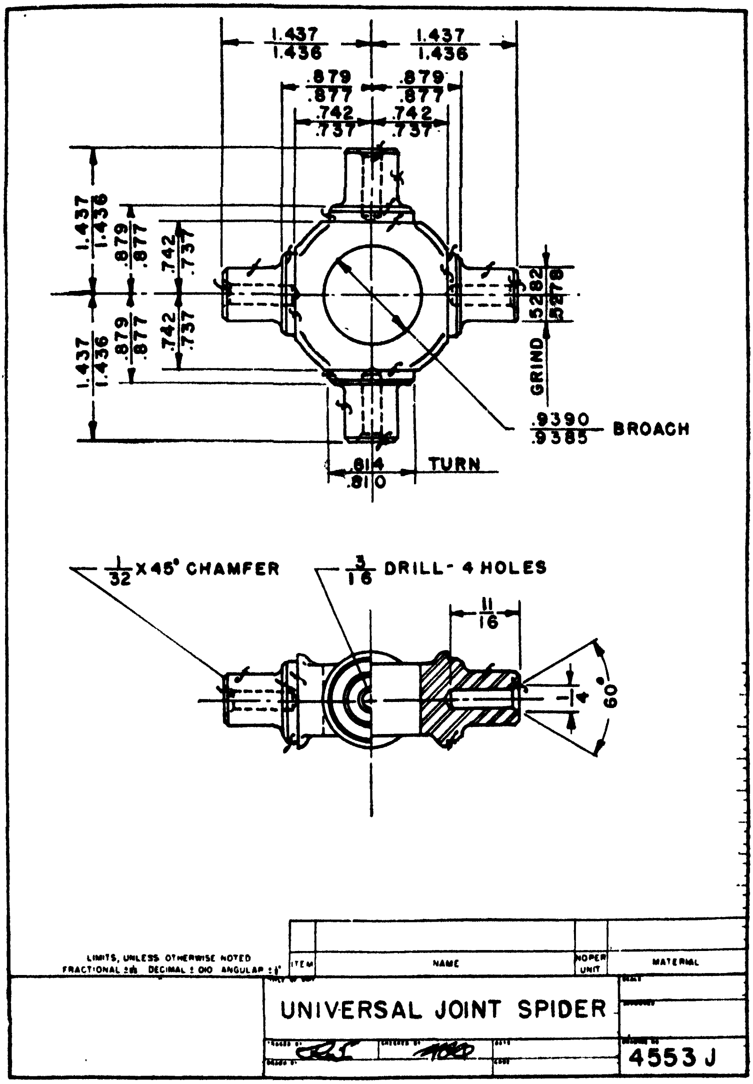


Fig. 139. Universal joint spider. (From Owen, *Introduction to Tool Engineering*, p. 39, Prentice-Hall, 1948.)

to suggest improvements in design to help manufacturing. In addition, minor changes may be requested to improve an accepted process. These may include:

1. Additions to a workpiece to:
    a. Control warpage.
    b. Control deflection.
    c. Add to strength to resist cutting forces.
    d. Aid in holding the workpiece.
    e. Aid in driving the workpiece.
    f. Aid in location.
    g. Prevent mutilation.
    h. Conform to the natural actions of the tools.
2. Changes to reduce:
    a. Tooling costs.
    b. Operator skill.
    c. The number of steps to make a part.
    d. Material costs.

Functional areas of a part should receive more careful treatment than others and usually have appropriate restrictions placed upon them for that purpose. Accordingly, they are logical areas from which to locate and gage in manufacturing. The areas used for the latter purposes are called critical areas. Some functional areas make better critical areas than others. General indicators of critical areas are:

1. The presence of base lines.
2. Surfaces dimensioned with close tolerances.
3. Requirements of surface finish or flatness.

Tests which are useful in selecting the best critical areas are those for:

1. Arithmetical superiority.
2. Geometrical superiority.
3. Mechanical superiority.

Thus, critical areas are not always those associated with small tolerances. In fact, critical areas are present on all parts with functions, even though the functions do not require close tolerances. The critical areas are those that must receive relatively careful treatment to satisfy specifications and also offer advantages for locating and gaging.

QUESTIONS

1. What is the first step of planning and what does it imply?

2. In what form are specifications for a job received?

3. What may manufacturing specifications include?

4. Is it important that all statements of manufacturing requirements be explicit? Why?

5. Why should the tool engineer want to point out improvements in product design?

6. What kinds of design changes may be found to improve specific processes?

7. What may be done to help in holding, driving, or locating some pieces?

8. Suggest changes that may be helpful in reducing tooling costs.

9. Suggest changes that may help decrease the number of steps in a process.

10. Is all the information needed about the material for an article always found in its design data? When not?

11. Where does information about the quantity of production usually come from?

12. What are the critical areas of a part? What relation do they have to functional areas?

13. State and give examples of three general indicators of critical areas.

14. Describe three tests for pertinent critical areas.

15. Are critical areas always associated with very close tolerances? Explain.

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11 DETERMINING THE OPERATIONS OF A PROCESS

◆ ◆ ◆

GENERAL CONSIDERATIONS

The next logical step after determining what must be done is to ascertain how it can best be accomplished. Several methods are often available. In a machine shop, a piece may be turned on an engine lathe, turret lathe, or automatic. A plane surface may be machined on a shaper, milling machine, broaching machine, or on one of a number of the other machine tools. In a foundry molds may be made by hand or on a machine. One casting may be made in a flask or several. The problem in every case is to find the best method under the prevailing circumstances. As has been explained, economic considerations run throughout all such problems and must never be forgotten. But there are other factors as well, and consideration of them is one of the purposes of this chapter.

The best way of doing any one part of a job can seldom be found by contemplation of the one item alone. Related components of a task are usually done most efficiently in some connected manner, often together in one operation. Thus, to find the best method, a decision must usually be made as to how the individual items are to be grouped or combined. Shall the requirements be satisfied in separate operations, or shall they be met, a number at a time, in larger operations? If combined, how far shall a consolidation be carried?

As was shown in Chap. 10, to find out what must be done to make an article means to discern what items are required and what their relative importance is. That leads to a list of the basic steps needed to do the job, but not in the most desirable order or array. To group the items effectively, three steps must be taken. They are:

1. Classify the items according to types of operations found in fundamental processes or procedures.

2. Separate the items of each class into groups to conform to limitations of equipment or practices of each field of endeavor.
3. Determine for each group the composition of the operation or operations most suitable.

In all cases, treatment is not as detailed as that just described. For simple parts all steps may not be necessary, and the conclusion may be so obvious that it is reached without conscious analysis. For complex situations, though, the separate steps afford a logical way of setting-up operations.

The selection of machine tools is in most cases a necessary part of the determination of operations. Where work is mechanized, the way it is done is in a large part governed by the action of the machinery.

CLASSIFICATIONS ACCORDING TO TYPES OF OPERATIONS

Operations typical of processes or procedures

In manufacturing, and particularly in metal processing, 6 classes of operations are common. Each class includes a set of related activities that contribute to a distinct process phase. Arrangement in this manner calls for:

1. Founding operations.
2. Enterprise protection operations.
3. Critical manufacturing operations.
4. Placement operations.
5. Tie-in operations.
6. Assembly operations.

Founding operations are those by which material, most frequently but not necessarily metal, is molded, formed, forged, and so forth, to a desired shape. Products of such operations may be castings, forgings, bars, or strip stock and are usually the rough stock for subsequent machining or manufacturing operations. They mostly constitute highly specialized processes in themselves and are not performed in the majority of manufacturing plants. For example, there are few steel mills compared with the number of metal fabricators, and most factories purchase steel in commercial forms. Even castings and forgings are frequently secured from outside sources. Accordingly, founding operations usually do not appear in most process plans, although their influence is likely to be quite important, and they must be understood and recognized.

Enterprise protection operations are those that control or expedite the manufacturing routine and protect the interests of the enterprise. They include receiving, storing, and various forms of inspection (receiving, metallurgical, process, and final inspection.)

Some of the factors that influence the nature of inspection operations and their placement within the process are:

1. The degree of accuracy required.
2. The skill of the workmen.
3. The size of the plant.
4. The quality of the raw material.

Critical manufacturing operations are those concerned with treatment of the critical areas, the surfaces that provide the workpiece, in its holding device, with a definite location. A cardinal principle of process engineering is to establish the critical areas first. Since critical operations are performed usually upon rough pieces, the following rules are of importance in appraising and analyzing their content and scope:

1. The variations of the rough workpiece as it is received from the founding operations or process must be known so that provision can be made for adequate stock removal from all surfaces.

2. The rough workpiece must be located to insure:

a. That any surfaces that are not to be finished will not be askew. Many parts are designed to have only certain surfaces machined. Sections may be bounded on one side by a finished surface and on the other by a rough surface. Provision must be made so that the cuts are not taken so that the sections will be too thin, or too thick, or vary beyond the allowable limits. Rough surfaces must not run out excessively nor offer interference when the part is performing its intended function.

b. Uniform stock removal (workpiece to workpiece) from all finished surfaces so as to insure that surfaces will be cleaned.

3. All critical areas and as many related surfaces as feasible should be machined from the same locators, preferably in one setting, to get the most accuracy. Errors introduced by resetting the workpiece are eliminated by performing as many related cuts as circumstances, knowledge, and imagination allow.

Placement operations are those by which the nondimensional requirements are met, such as material hardness and toughness, plating, protective coatings, cleaning, shot peening, burring, and so on. Many times one or a group of placement operations represent an auxiliary process within the entire process. Procedure and position within the sequence are usually dictated by techniques, skills, or practices. Plating, for instance, is a chemical process requiring that the objects be subjected to definite preparation and treatment. As another example, localized casehardening is accomplished by conventional techniques. By one method the areas to be left soft are carburized in an oversize condition and the excess stock is removed before hardening. By another method, the soft areas are copper-plated to exclude carburization and are deplated after the hardening quench. As a general rule, placement operations produce easily mutilated areas, and it is often desirable to perform them near the end of the process.

Many placement operations require detailed and specialized knowledge, which the process or tool engineer in general is not expected to possess. In many plants the process planner works with specialists in determining the required condition of the part as it enters and its characteristics as it comes out of the placement operations. In some places specialists may prepare outlines of standard procedures for placement operations, like the one shown in Fig. 140, for heat treatment of AMS 6250 steel. It is primarily the responsibility of the process engineer to apply to these operations the appropriate principles of process and tool planning and to establish their proper contributions to the process.

Tie-in operations are those whose sequence and method is dictated by the geometry to be achieved after the workpiece comes out of critical manufacturing operations and/or placement operations. The results from the tie-in operations must satisfy the needs of later placement operations or the specifications of the finished part. Cutting of gear teeth, finish grinding of surfaces, and drilling of noncritical holes are examples of tie-in operations. The following principles concerning tie-in operations serve to define their nature and relationship in the process:

1. In the tie-in operations, locate from the critical manufacturing areas for consistency and uniformity of control.
2. If the critical surfaces have been distorted by placement opera-

Dept. No.	Operation Description	Machine Name	Mach. No.
366	Degrease.	Spray washer	
366	Load carburizing pot.	Floor	
366	Transfer pot to furnace.	Electric crane	
366	Carburize - Specs.ES200 & ES235. Heat to 1650 F. 1.25 hr. Bring to heat 2.5 hr. at least.	15 x 30 homo. Carb. furnace	93 108 4342 4343
366	Remove pot from furnace and transfer to cooling pit.	Electric crane	
366	Cool in pit for 3 hr.	Controlled cooling pot	
366	Transfer pot from pit to floor.	Electric crane	
366	Unload pot.	Floor	
366	Load annealing pot.	Floor	
366	Transfer pot to furnace.	Electric crane	
366	Anneal - Spec. ES200. Heat 1300 F. 1.5 hr. Bring to heat, 1 hr. at least. 9.5 hr. bring down to 900 F.	25 x 36 Homo Carb. furnace	4338 4339 4340
366	Remove pot from furnace and transfer to cooling pit.	Electric crane	
366	Cool in pot for 3 hr.	Controlled cooling pit	
366	Transfer pot from pit to floor	Electric crane	
366	Unload pot.	Floor	
366	Clean off carbon.	Grinding stand	5160
366	Harden, Spec. ES200, 1475-1500 F.	Lindberg hydrizer	4432 4570 5271
366	Quench in Spec. ES10 oil.	Gleason quench Press	2290 6089
366	Vapor degrease.	Detrex degreaser	
366	Temper Spec. ES200. Heat to 300F. for 1 hr. and cool in air.	Draw furnace	2956 105
366	Shot blast 40 lb. max. press.	Amer.wheelabrator	
319	Check runout between centers 100% for shafts. (Insert concentricity specs.) Check spline size-10%.	Bench centers	ST171
366	Heat to straighten 10%. Heat to 1475-1500 F.	Lindberg hydrizer	4432 4570 5271
366	Quench in Spec. ES10 oil - 10%.	Gleason press	4171 6080
366	Vapor degrease 10%.	Detrex degreaser	
366	Temper 10% Spec. ES200. Heat to 300 F. for 1 hr. and cool in air.	22 x 26 Homo Draw furnace	2950 2956 105
366	Shot blast 40 lb. max. press. 10%	Amer. wheelabrator	
319	Check runout 10% (Insert concentricity specs.)	Bench centers	

Fig. 140. Standard procedure to carburize and harden A.M.S. 6250 steel.

tions (like heat treatment) re-establish the critical areas by going back to the original founding process workpiece locators or to secondary locating surfaces, reliably related to the critical areas. Thus, if a casting is heat-treated to relieve strains, the critical surfaces are probably warped and should be remachined to restore their truth by relocating on the same spots from which these surfaces were originally located.

3. All workpiece geometry should be accomplished, where finishes and tolerances permit, while the workpiece is in the most workable condition. As an example, as much of the machining should be done on a part as possible before chrome plating to avoid marring the plated surfaces. Also, where distortion is not of importance, drilling is often desirable before heat treatment and consequent increase in material hardness.

4. The extent of workpiece variation coming from the placement operations to the tie-in operations should be definitely ascertained and controlled. For instance, it is desirable to determine workable limits of distortion from heat treatment and standardize on those limits to be able to qualify the errors in the tie-in operations that follow.

Assembly operations, as the name implies, are those in which parts are put together to form the desired mechanism or one of its larger components.

The significance of the initial classification

The manner of satisfying a required item (like turning a diameter, finishing a plane surface, or heat-treating the material to a desired hardness), usually has an obvious place in only one of the six process classifications. Although such an allocation does not, by itself, designate specifically the operation in which any one item is to be included, it does provide a basis for recognizing related items and establishes a first degree of order from a chaotic aggregate of requirements.

OPERATIONS CLASSIFIED ACCORDING TO SPECIALTIES

The work to be done within the province of any fundamental class of operations (founding, placement, critical, or tie-in operations) normally can be further segregated according to natural or conventional activities within the field. This division is natural, largely because of the comparatively limited range of action of even the most versatile machines and equipment. As an example in the machine shop, there are machine tools, such as those of the lathe family, best suited for cylindrical parts, others like milling machines and shapers more adaptable for plane surfaces, and drill presses for holes. For heat treatment, in the placement operation class, certain equipment is suited for carburizing and other for heating steel in a neutral atmosphere prior to quenching. Thus, by the recognition of specialties of performance, the concomitance of various items can be ascertained within close limits. This does not imply that all the individual items that prove to be related shall necessarily be combined into one operation. It only indicates the similarity of certain actions, and the exact manner in which they are to be combined into operations is still to be determined by other considerations.

THE COMBINATION OF SIMILAR ACTIVITIES INTO OPERATIONS

Economic considerations of work allotment

After the necessary work units have been segregated into classes and then into groups, they must be arranged into one or more operations within each group. Thus, operations must be devised to get the work done in the shortest possible time with the equipment allowed for the project. Two conditions must be compromised to achieve that end. Generally, savings in time result from combining as many job details on one machine or into one operation as circumstances warrant. Loading and handling time are then reduced and the errors resulting from resetting the workpiece are minimized. On the other hand, if the increase in duties places too much responsibility on one worker, the advantages of specialization may be sacrificed. The more done in one operation, the more complex, specialized, and expensive is the equipment. Fixed charges rise to offset savings in direct costs. A favorable balance must be found between gains and losses.

The selection of machines

Most manufacturing, particularly metal processing, is so inalterably dependent upon machinery that the form of an operation cannot be analyzed independently of the machines and equipment that make it possible. A decision as to what machine to use is usually equivalent to specifying the number of steps to be taken in the operation that employs it. Thus, the problem of combining related items of a process into operations is also one of selecting machines and equipment. Many considerations may influence that selection but normally only a few of them are pertinent to any one case. The important ones should be known so that they may be taken into account where applicable. They are:

1. *The nature of the work to be done* that involves the following factors:

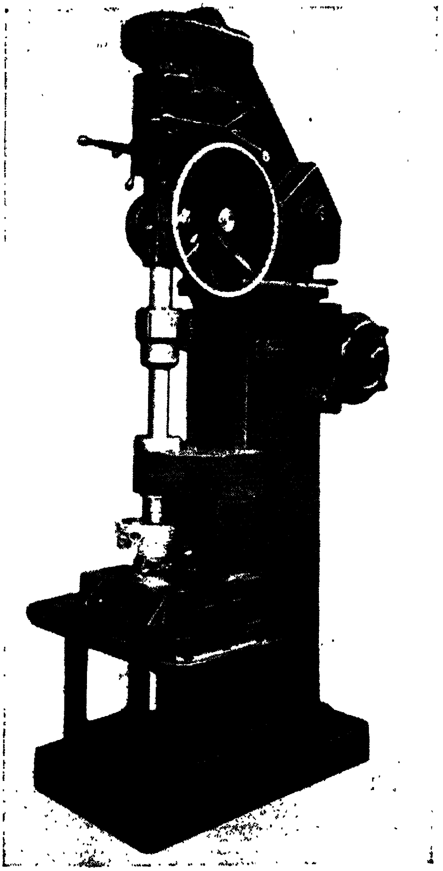


Fig. 141. A single-spindle drill press equipped with special boring bar guide, and fixture for boring 2¾-in. to 3⁷⁄₁₆-in. diameter motorcycle cylinders. With this installation, machine time is lost while the operator is loading and unloading the fixture. Also, only one cut is taken at a time. However, the investment in special equipment is comparatively low and is justified for medium quantities or production in lots where a number of sizes or models make frequent change-over necessary. (Courtesy Barnes Drill Co., Rockford, Ill.)

a. *The number of aspects presented.* Specifically for metal cutting this means the number of related surfaces to be machined, which primarily determines the number of choices presented in the formation of an operation. If there is only one surface, there can be only one operation. If there are two surfaces, they may be done

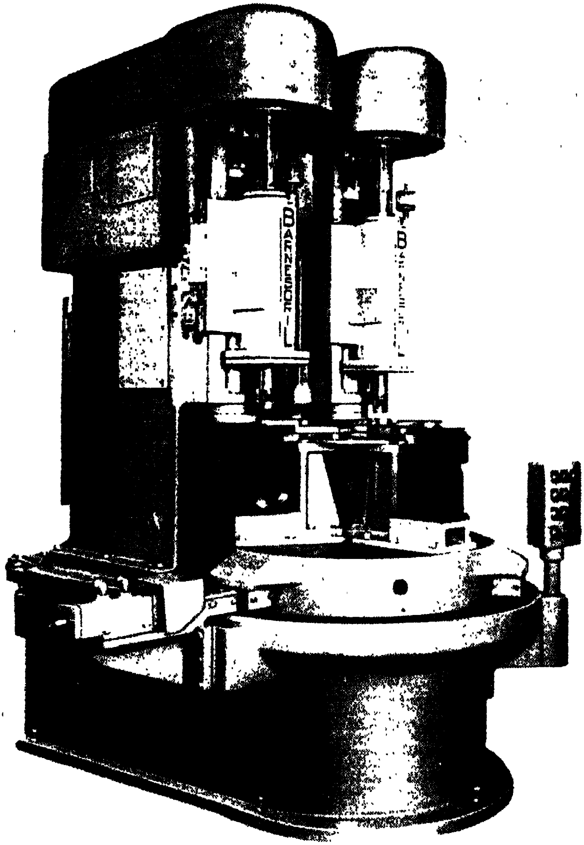


Fig. 142. A vertical two-spindle precision boring machine for rough and finish boring 2½-in. diameter cylinders. With this installation, the loading and unloading is done while the machine is operating, and two cuts are taken at once. However, the comparatively heavy investment must be sustained by the production of a large quantity of parts manufactured virtually continuously. (Courtesy Barnes Drill Co., Rockford, Ill.)

separately or together; thus there are two choices. For 3 surfaces there are 5 alternatives; for 4 surfaces, 15 alternatives, and so on. Often only a few alternatives are of practical importance, so the number of possibilities may or may not have full significance in every case.

As an example, consider a single cylinder engine block in which the cylinder must be rough- and finish-bored. In reality there are two machining cuts. The cuts may be taken separately, like in Fig. 141, or at the same time as shown in Fig. 142. In contrast, for a multiple cylinder block the cuts may be taken individually, as indicated in Fig. 143; all cylinders rough-bored together on

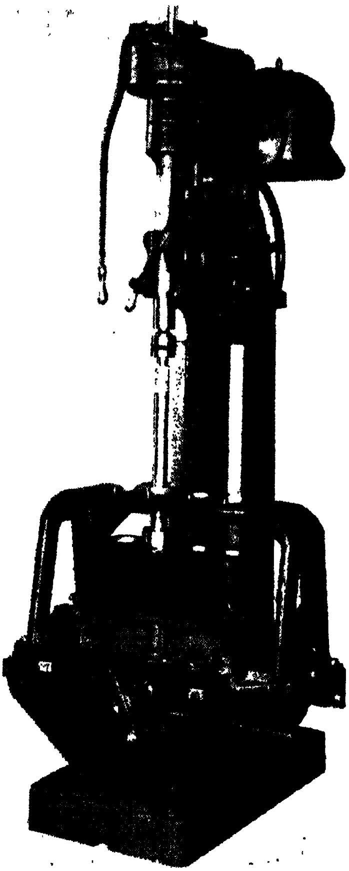


Fig. 143. Cylinder boring machine for machining one cylinder at a time. An adaptation of a single-spindle drill press, this unit is applicable to low production, such as the reconditioning of cylinder blocks. (Courtesy Barnes Drill Co., Rockford, Ill.)

one machine and then finish-bored on another, like in Fig. 144; or conceivably, but not probably, in any one of a number of other alternative ways. What is shown, however, is that in the two cases the methods adopted for quantity production differ, largely because the variety of offerings in one instance is not present in another.

b. *The diversity of the aspects.* Specifically, this means the difference in size of the surfaces in a group. For instance, several items under consideration may be holes all having the same diameter, or they may have different diameters. If the holes are all the same,

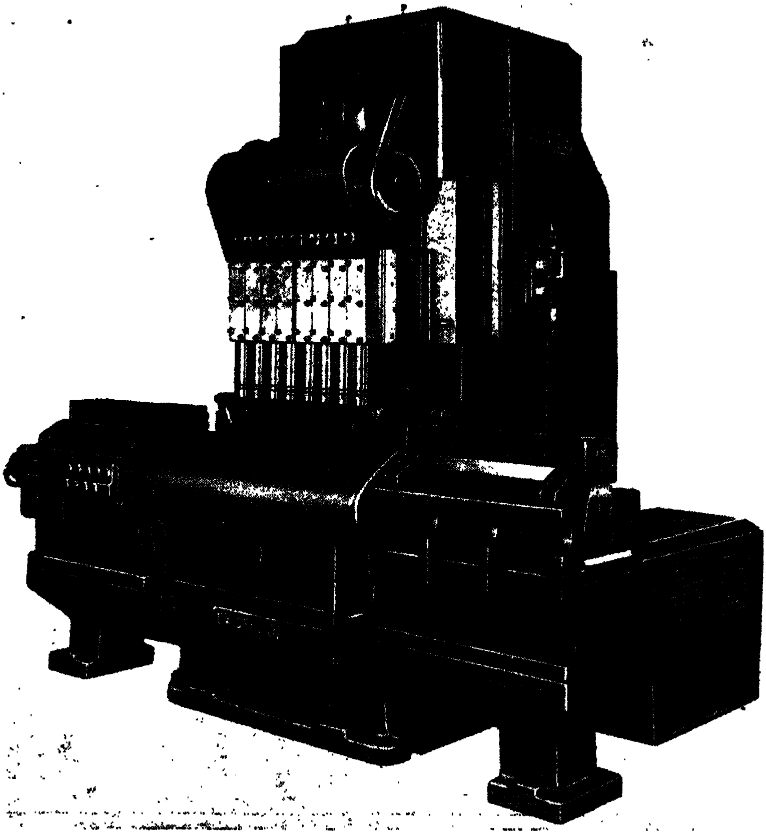


Fig. 144. A cylinder boring machine that bores all the cylinders in a block at the same time. Units of this type are used for large quantity production. (Courtesy Excello Corp., Detroit.)

greater opportunities for drilling them in one operation are presented. If holes of different diameters are to be drilled individually but in the same operation, several spindles may have to be used or means provided for changing the drills easily in one spindle. The necessary speed range may be difficult to find in one machine, if very

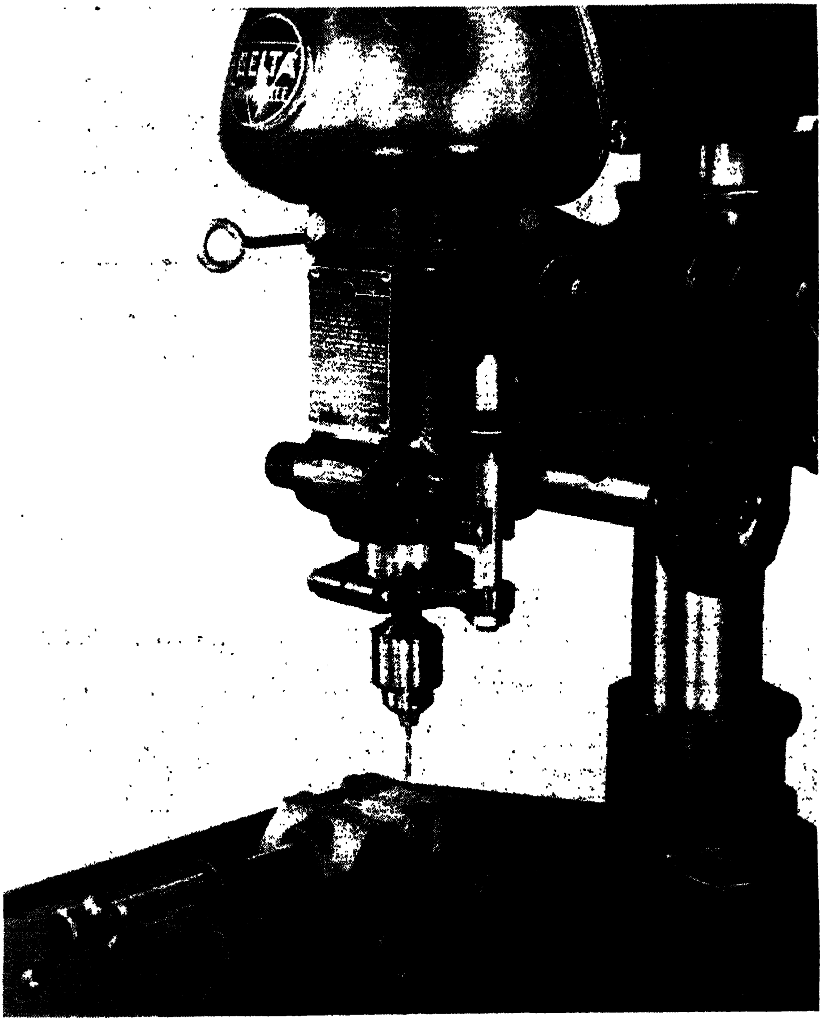


Fig. 145. A small sensitive high-speed drill press for holes up to ½ inch in diameter. (Courtesy Delta Manufacturing Div., Milwaukee.)

large and quite small drills must be used together. A drill press suitable for large holes may not be desirable for small ones, and vice versa, as indicated by the contrast between the machines of Figs. 145 and 146. Such difficulties are not encountered in planning an operation for drilling a number of holes of the same size.

To carry the illustration further, in addition to differences in diameter, holes may have a disparity in depth or some holes may require tapping and others countersinking, and so forth. Deep holes require different machine settings and oftentimes a different tech-

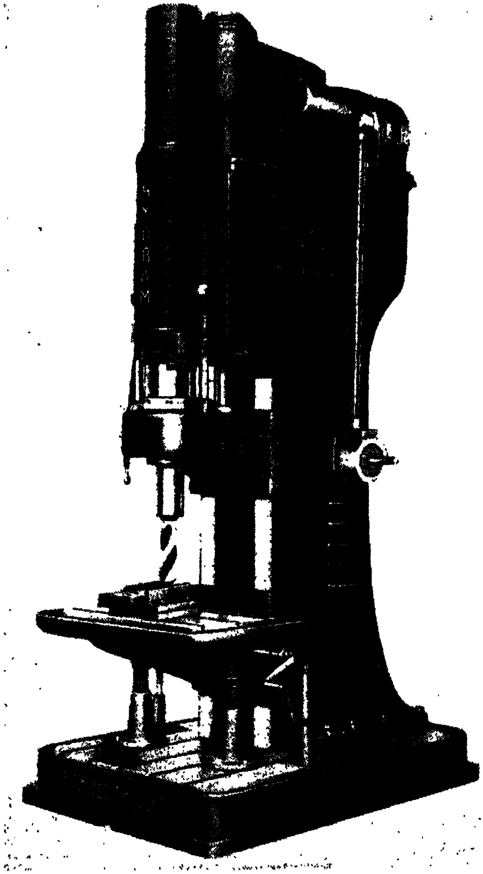


Fig. 146. A heavy-duty drill press, shown with a 4-in. diameter twist drill. (Courtesy Barnes Drill Co., Rockford, Ill.)

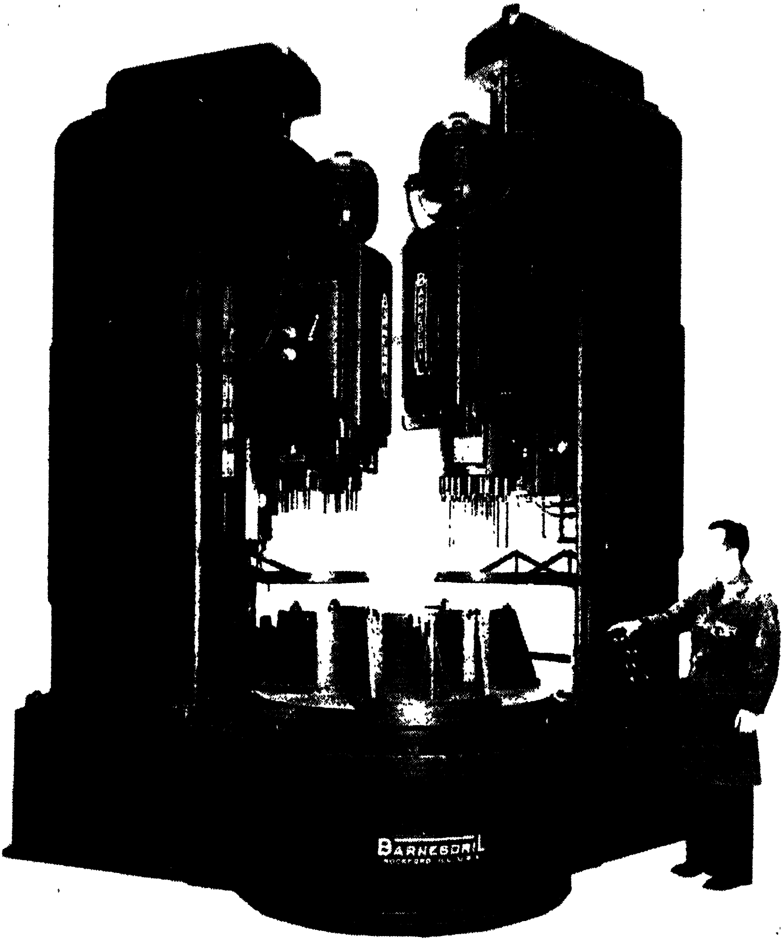


Fig. 147. A special vertical machine for countersinking and tapping holes in an aircraft propeller barrel. The holes are drilled on another machine. The operation of this machine is as follows:

1st station—load in fixture.
2nd station—countersink 8 holes (at left).
3rd station—lead screw tap 32 holes.

The fixture is indexed, after the heads retract, to carry the parts through the cycle. If it were not for this special equipment, this work on the barrels would probably have to be done in two or more operations. (Courtesy Barnes Drill Co., Rockford, Ill.)

nique, in order to clear the chips, from that of shallow holes. The machine of Fig. 147 illustrates how such diversity, even if mitigated by combinations provided by special machines, must be recognized in the design of the equipment, which has separate stations for different kinds of work.

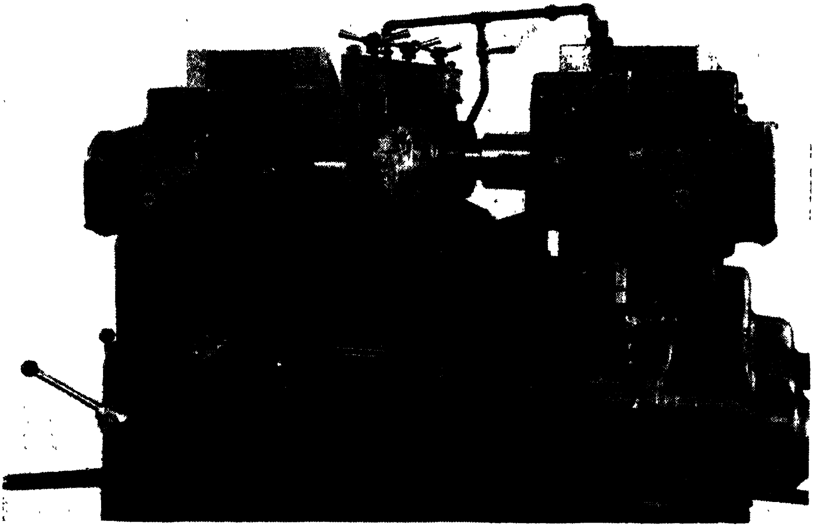


Fig. 148. Parallel sides of an aluminum cylinder block being finished on a standard production milling machine. (Courtesy Cincinnati Milling Machine Co., Cincinnati.)

In general, as the dissimilarity in items in a group becomes more pronounced, the tendency is to require a greater number of operations to perform them.

c. *The relative positions of the surfaces.* It is usually easier to machine parallel surfaces in one operation than oblique ones. If surfaces are not parallel, special arrangement of equipment is often necessary to accommodate them. This factor is illustrated in Figs. 148, 149, and 150.

d. *The dimensional tolerances.* The closer the tolerances, the more exacting the job. In some cases close tolerances may necessitate additional operations, as when grinding is a necessary addition to meet accuracy requirements. On the other hand, tight limits

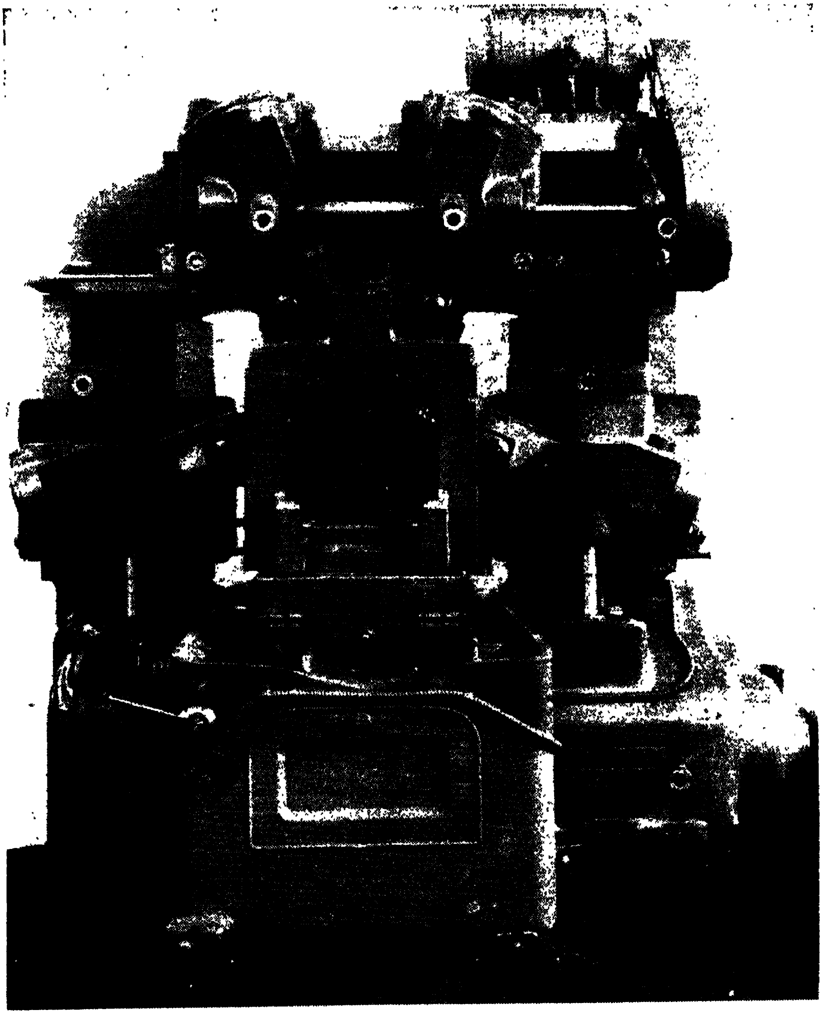


Fig. 149. Cylinder head contact faces and water-back surfaces of a cylinder block being milled simultaneously. Since these surfaces are not parallel, special spindle carriers are required on the milling machine. On a standard milling machine such as Fig. 148, the surfaces would have to be done separately with different fixtures to position the block for each surface. (Courtesy Cincinnati Milling Machine Co., Cincinnati.)

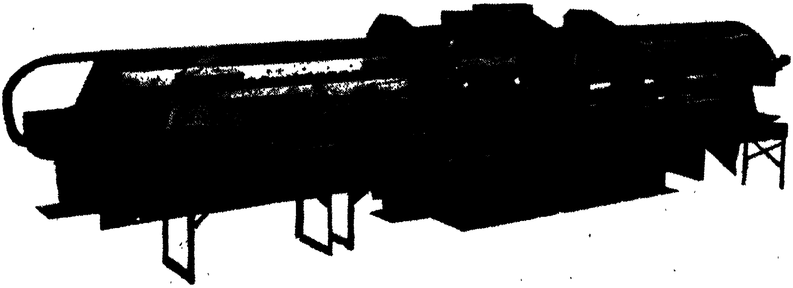


Fig. 150. Front view of a large double-acting horizontal side-broaching machine for machining bottom, top, valve chamber-cover face, and distributor pad on a six-cylinder engine block. This is representative of equipment used for very large quantities. Output is 60-cylinder blocks per hour. (Courtesy Cincinnati Milling Machine Co., Cincinnati.)

Fig. 151. A machine for drilling in one station and reaming in another station. Thirty-eight holes in a section of an aircraft crankcase. The advantages of simultation is apparent in this installation. Less evident, but nevertheless present, is the advantage of accuracy in the relative placement of the holes derived from the operation of reaming them together. (Courtesy Wright Aeronautical Corp., Wood Ridge, N.J.)

may dictate the simultation of the cuts of a number of surfaces so that the dimensions between the surfaces can be held closely by all being machined at once. An example of this is found in the drilling or reaming of a number of holes at once and in the same jig to maintain close center distance, as indicated by Fig. 151. In Fig. 152 a line of grinding machines performs several passes on pins to produce required accuracy.

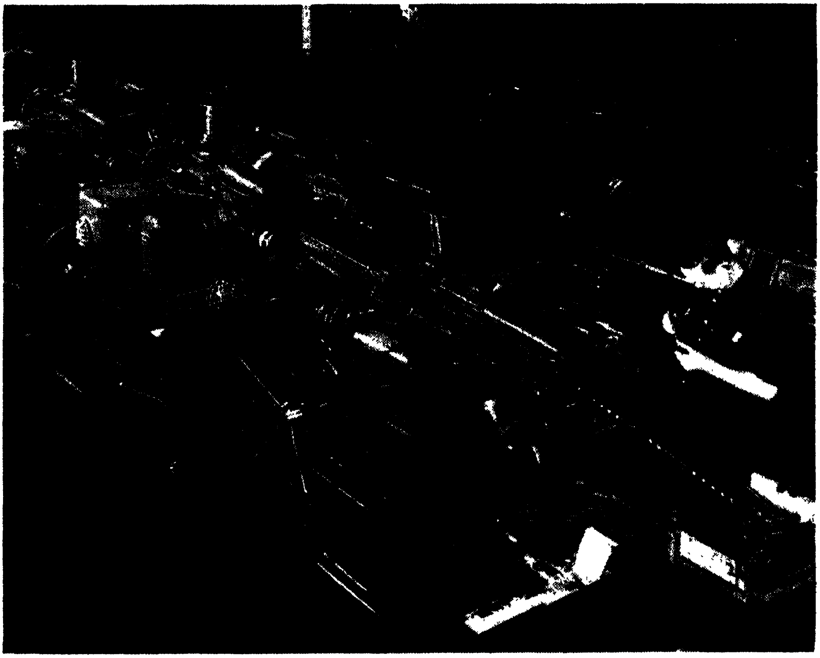


Fig. 152. A line of centerless grinding machines with interconnecting conveyers for continuous production of pins to close limits of dimensions and finish. (Courtesy Cincinnati Milling Machine and Grinders, Inc., Cincinnati.)

2. *The characteristics of the workpiece,* which involves:

a. *The size of the workpiece.* Small work does not have much significance from this standpoint. Large work, however, requires special handling effort because of its bulk and weight, and the tendency is to reduce this effort by employing a minimum number of operations. The logical choice for large castings is a machine on which as many cuts as possible can be taken without moving the workpiece. An example of this is given in Fig. 153.

b. *The material,* not only what it is, but also its state. Very hard material requires different treatment from soft material. Grinding may be essential even to remove stock in some cases. The working of tough material consumes more power, and equipment may have to be selected accordingly.

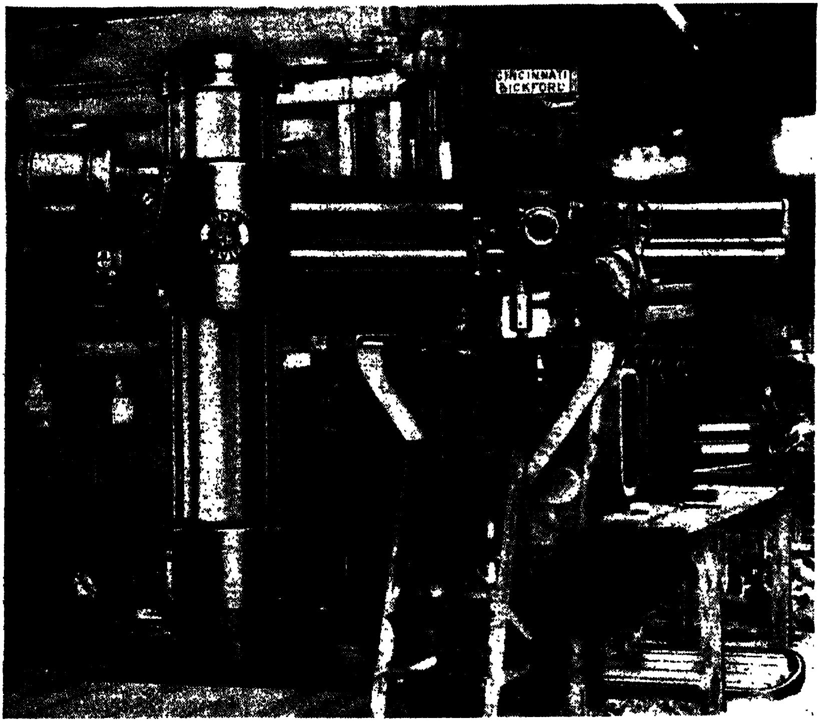


Fig. 153. An example of a large workpiece that is not easily moved and reset. This is a diesel-engine center frame on which is performed a total of 684 drilling operations including 2½-in. spot facing. All formerly required 24 hours, but when placed on the radial drill and done in one operation, were completed in 17 hours. (Courtesy Cincinnati Bickford Tool Co., Cincinnati.)

3. *The tenure of the operation,* which determines the extent to which advantage may be taken of benefits offered. Usually the greater the production demand, the greater the justified investment. In fact, the influence of demand is so strong as to be able to transcend most of the other considerations. The quantity of production primarily determines whether standard equipment shall be used or

whether special devices can be developed for a particular job. As an example, the single-spindle drill press of Fig. 143 with its comparatively inexpensive additions is slow by some standards, but is all that is justified for a low output, as might be found in a small repair shop. In contrast, a special machine that bores all the cylinders in a block, like that of Fig. 144, is worth-while for high production.

Another example of the influence of quantity production is seen in the comparison of Fig. 141 and Fig. 142.

Certain functions although related often are sufficiently distinct to receive separate treatment conventionally, like drilling, chamfering, reaming, facing, and tapping. However, under the urge of

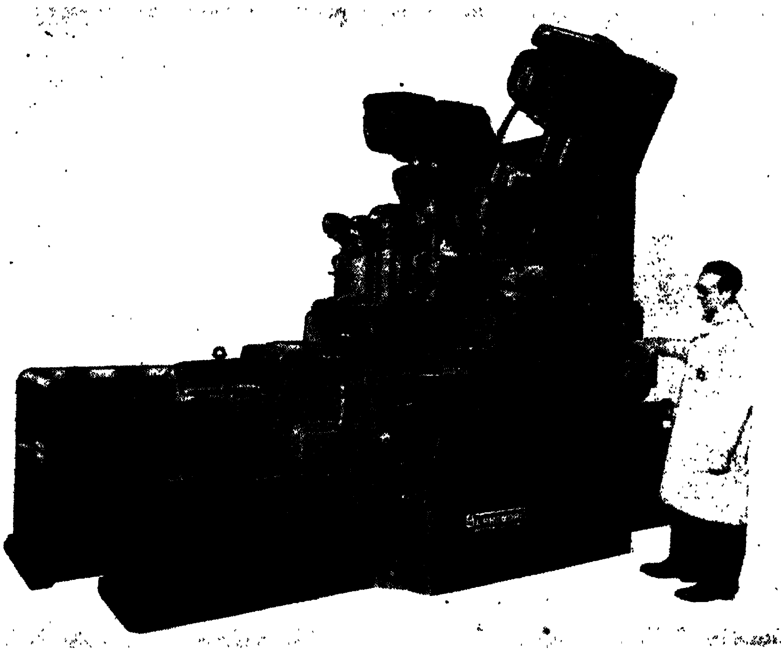


Fig. 154. A special hydraulic unit production-type machine for drilling, chamfering, reaming, facing, and tapping a cast-iron automobile transmission case. The work pieces in the multiple fixture are indexed through seven stations and are acted upon by six multiple spindle heads. One station is unloaded and loaded while the work is being performed. This type of installation is only feasible for very high and continuous production. (Courtesy Barnes Drill Co., Rockford, Ill.)

quantity production, the combination of these functions may be warranted as shown in Figs. 147 and 154.

Even the almost fundamental concepts of machine tool characteristics may be cast aside as a result of the demands of high production. As a general rule, machine tools perform limited functions separately, like milling and drilling. Yet, if circumstances warrant, these distinctions may be contravened as illustrated by Fig. 155.

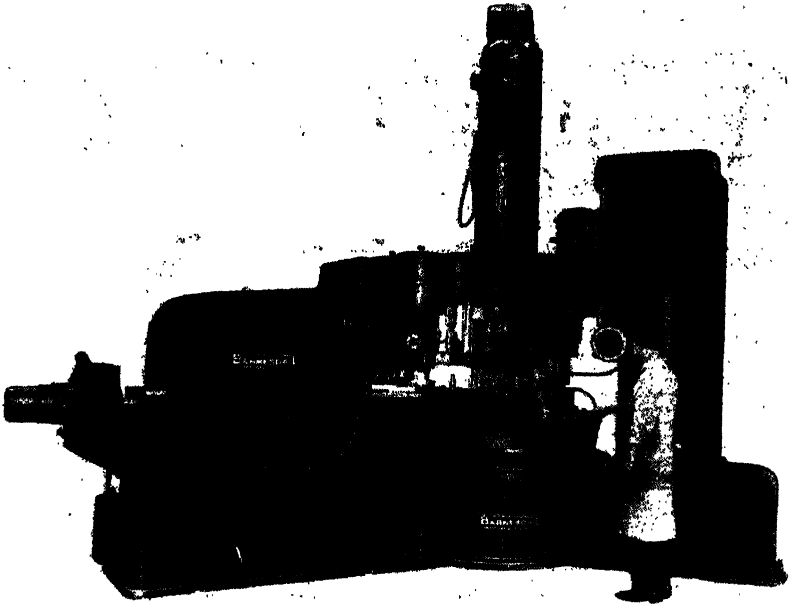


Fig. 155. A special machine for milling, drilling, counterboring, reaming, and tapping bottoms of single-, double-, and four-cylinder crankcases. This machine consists of a two-spindle milling unit, one vertical unit with 20 spindles, one ten-spindle individual leadscrew tapping unit, and a seven-station rotary power index table. (Courtesy Barnes Drill Co., Rockford, Ill.)

Another example of ingenious simultation, not uncommon, is found in the combination of the operations of different parts. A machine designed for that purpose is shown in Fig. 156.

An example of a high degree of mechanization for producing large quantities is the transfer machine of Fig. 73. Specifically, the factors affecting this consideration are:

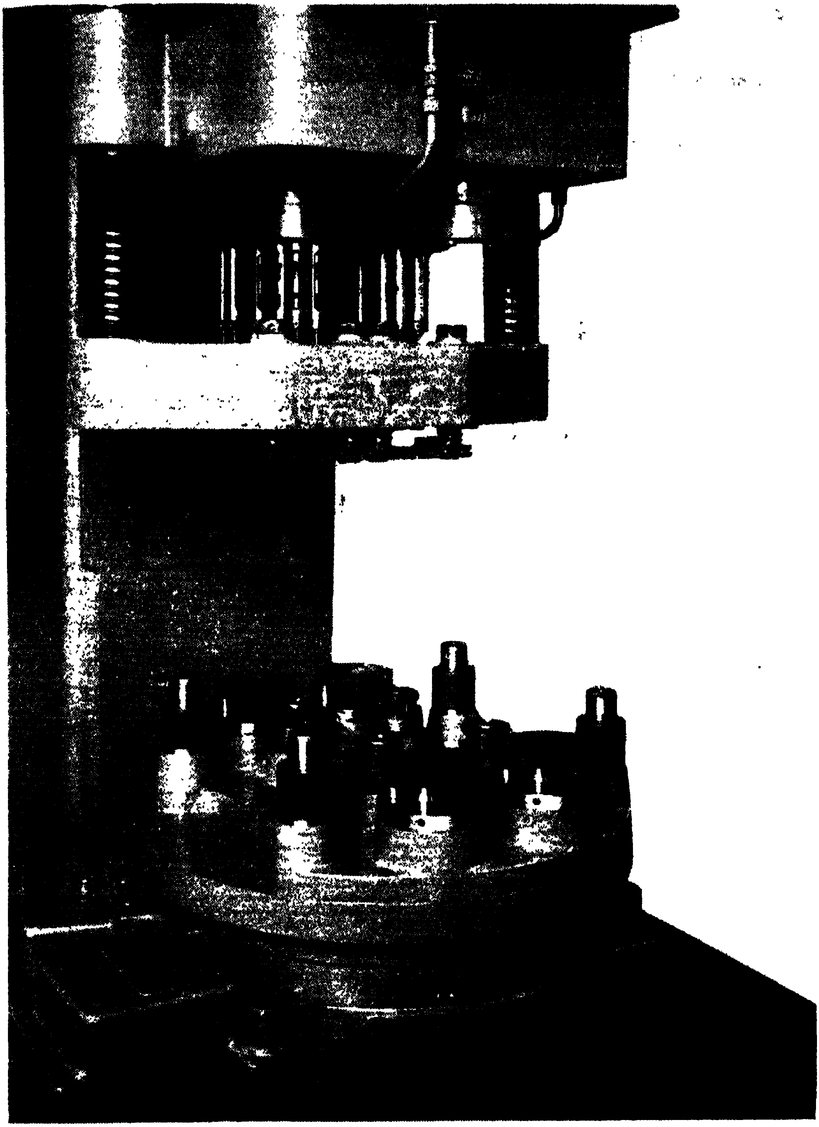


Fig. 156. A special production-unit machine arranged with 26-spindle auxiliary bushing plate and indexing table with four-place fixture for holding two each of two different parts while drilling a total of 26 holes. A production of 300 pieces per hour is realized. (Courtesy Barnes Drill Co., Rockford, Ill.)

a. *The rate of production* as expressed by the quantity of parts to be made over a period of time.

b. *The life of the product.*

c. *The type of production,* whether batch, semi-continuous, or continuous. Small lots tend to favor standard machines and a few operations to reduce setup time. Continuous production is usually associated with large quantities that often justify special machinery.

d. *The trend or future of the enterprise.*

4. *The costs of the project.* That selection is mandatory which assures the lowest unit cost, other conditions being equal. The unit cost is the total cost for a period, divided by the usable output for that period. The factors which give rise to the cost are:

a. *The cost of the machine* as reflected in its capital assessments.

b. *The cost of the labor* to run the machines.

c. *The cost of maintenance.*

d. *The cost of tooling.* For instance, a milling machine may take the least time for finishing a surface on a casting, but the shape of the piece is such that a special fixture is necessary for holding it. A planer may take more time but may be preferable if it can be set up to obviate a fixture, especially if only a few pieces are required.

e. *The cost of setup and tear down.* An example of a difference in this factor is found in a comparison between a turret lathe which may require a setup time of 2 hours for a job and an automatic screw machine requiring 6 hours for setup for the same task.

f. *The floor space occupied.*

g. *The versatility of the machine* or its promise of sustained value under different conditions. A special machine usually must be paid for entirely from the production of the article it is designed to produce. A standard machine adapted to a job may require a charge for only part of its cost against the job since it may be usable for other work also.

5. *The capacity required of the machine,* including

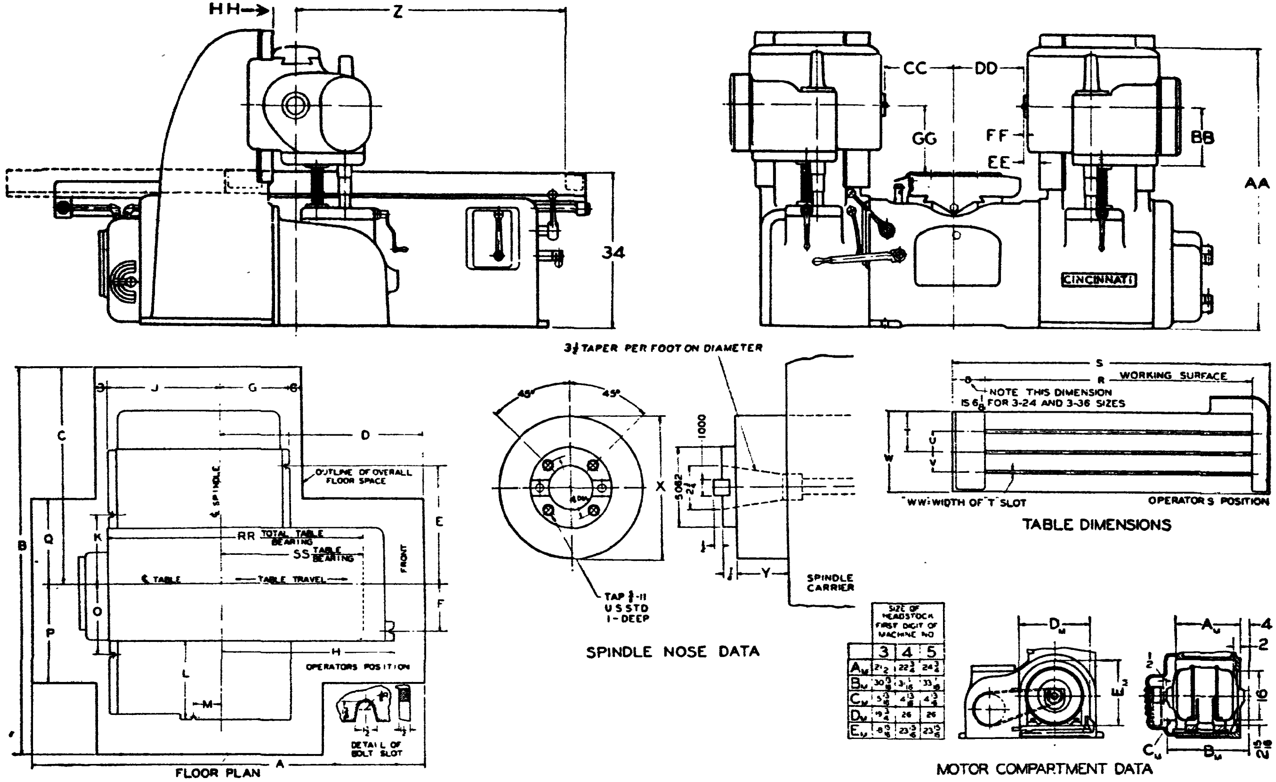
a. *The ability of the machine* to do the proposed work in an efficient manner. Thus, the turning of a shaft obviously calls for some sort of lathe, forming of sheet metal for some type of press. Then within each general class of machines there are often two or more types for different purposes. For instance, one type may be intended for general purpose work, another type for repetitive work.

This factor usually limits the choice to a narrow field from which the actual commitment is made on the basis of other considerations.

b. *The range of the machine* to enable it to handle the size of workpiece and cover the desired area. Machines with comparable ratings in other respects may vary greatly in the size of work they will take. For instance, one manufacturer makes a line of four presses rated around 250 tons capacity each, but all differ in size, length of stroke, and working distance. The smallest is a coining press about 10 ft tall and weighing 12,000 lb. It has a 2 in. stroke and works through ⅛ in. The short stroke is obtained through toggles, and the maximum force is realized at the bottom of the stroke. A general purpose press of the same tonnage capacity weighs 24,000 lb and is half again as high as the first. It has a 12-in. stroke and a 5-in. working stroke. In the same tonnage range is a heavy duty press weighing 30,000 lb, with an 18-in. stroke and an 8-in. working stroke. The largest press in this line with 250 tons capacity is a double-acting press weighing 145,000 lb. Its outer ram is toggle-driven and the inner ram crank-driven. It has a 36-in. stroke, a 16-in. drawing stroke, and is primarily used where the largest force must be exerted at some distance from the bottom of the stroke. The motor requirements go up in general proportion to the size.

Most manufacturers furnish, in their catalogues or otherwise, detailed charts and specification sheets from which data may be obtained covering the range and capacity of each machine. A specification sheet for one make of manufacturing milling machine is shown in Fig. 157. For the various sizes of machines, such data as table size and travel, clearance distances, speed, feeds, and motor size are given. Such information is not only helpful in selecting the machine, but also as a guide for designing the tools which go on it.

c. *The ruggedness and strength of the machine* or the ability of the machine to carry the load that must be placed on it. A machine may have to be light or heavy, depending upon the weight of the workpiece or the forces resulting from the cutting or forming operation. As has just been shown machines rated to deliver the same force may differ in range and size and also in ruggedness and strength. Also, machines having the same range may differ in other respects. For instance, No. 2 plain milling machines all have the range to cover about the same working area. Yet, some machines of that size are light in construction, designed for loads that can be served



	SIZE OF HEADSTOCK FIRST DIGIT OF MACHINE NO		
	3	4	5
A_M	21½	22¾	24¾
B_M	30 3/8	31 1/16	33 7/16
C_M	5 3/16	4 13/16	4 3/16
D_M	19¾	26	26
E_M	18 13/16	23 5/16	23 15/16

Fig. 157

Mach. Size	Table Travel	A	B	C	D	E	F	G	H	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA	BB	CC		DD		EE	FF	GG		HH	RR	SS	WW
		Max																							Max	Max			Max	Min	Max	Min			Max	Min				
3-24	24	78	90 7/16	47 3/8	39 9/16	30 11/16	10 9/16	16	29 11/16	27 1/4	15 11/16	19	8 1/2	27	17 1/16	27	23	39	49 1/2	6	2 7/8	2 7/8	12	7	4 11/16	33 11/16	55 11/16	14 1/8	9 7/8	5 7/8	8 1/2	4 1/2	3 13/16	1 5/16	12	5	4 1/4	42 1/2	22 1/4	11/16
3-36	36	100	90 7/16	47 3/8	50 9/16	30 11/16	10 9/16	16	29 11/16	27 1/4	15 11/16	19	8 1/2	27	17 1/16	27	23	50	60 1/2	6	2 7/8	2 7/8	12	7	4 11/16	44 11/16	55 11/16	14 1/8	9 7/8	5 7/8	8 1/2	4 1/2	3 13/16	1 5/16	12	5	4 1/4	42 1/2	22 1/4	11/16
34-36	36	106	94 13/16	49 3/4	47 7/8	33 1/16	12 9/16	16 1/4	38	36	18 1/16	23 5/8	12 3/16	29	19 1/16	29	25	53 1/8	65 1/2	8	3 3/4	3 3/4	16	7	4 11/16	41 23/32	55 11/16	14 1/8	11 7/8	7 7/8	10 7/8	6 7/8	3 13/16	1 5/16	12	5	4 1/4	59 1/2	30 1/2	11/16
34-48	48	130	94 13/16	49 3/4	59 7/8	33 1/16	12 9/16	16 1/4	38	36	18 1/16	23 5/8	12 3/16	29	19 1/16	29	25	65 1/8	77 1/2	8	3 3/4	3 3/4	16	7	4 11/16	53 23/32	55 11/16	14 1/8	11 7/8	7 7/8	10 7/8	6 7/8	3 13/16	1 5/16	12	5	4 1/4	59 1/2	30 1/2	11/16
35-48	48	130 5/8	99 11/16	52 5/8	59 3/16	35 15/16	14 9/16	16 1/4	48 7/16	36	20 15/16	23 5/8	12 3/16	31	21 1/16	31	28	66 1/8	78 1/2	10	5	5	20	7	4 11/16	53 1/4	55 11/16	14 1/8	13 7/8	9 7/8	13 3/4	9 3/4	3 13/16	1 5/16	12	5	4 1/4	76	40 13/16	11/16
35-60	60	154 5/8	99 11/16	52 5/8	71 3/16	35 15/16	14 9/16	16 1/4	48 7/16	36	20 15/16	23 5/8	12 3/16	31	21 1/16	31	28	78 1/8	90 1/2	10	5	5	20	7	4 11/16	65 1/4	55 11/16	14 1/8	13 7/8	9 7/8	13 3/4	9 3/4	3 13/16	1 5/16	12	5	4 1/4	76	40 13/16	11/16
36-72	72	178	103 3/4	54 11/16	83 7/16	38	16 9/16	16 1/4	62 3/8	36	23	23 5/8	12 13/16	33	23 1/16	33	30	89	101 3/8	12	6	6	24	7	4 11/16	77 1/2	55 11/16	14 1/8	15 7/8	11 7/8	15 13/16	11 13/16	3 13/16	1 5/16	12	5	4 1/4	102	54 7/8	11/16
36-90	90	214	103 3/4	54 11/16	101 7/16	38	16 9/16	16 1/4	62 15/32	36	23	23 5/8	12 3/16	33	23 1/16	33	30	107	119	12	6	6	24	7	4 11/16	95 1/2	55 11/16	14 1/8	15 7/8	11 7/8	15 13/16	11 13/16	3 13/16	1 5/16	12	5	4 1/4	102	54 7/8	11/16
4-36	36	105 5/8	107 1/4	53 1/8	51 5/16	34 5/16	12 9/16	19 11/16	41 7/16	32 9/16	18 9/16	23 5/8	8 3/4	29	19 1/16	29	25	53 1/8	65 1/2	8	3 3/4	3 3/4	16	8	6 11/32	45 11/32	62 7/8	12 1/4	12	6	11	5	3 23/32	23/32	16 1/2	5 3/4	5 1/2	59 1/2	33 13/16	11/16
4-48	48	129 5/8	107 1/4	53 1/8	63 5/16	34 5/16	12 9/16	19 11/16	41 7/16	32 9/16	18 9/16	23 5/8	8 3/4	29	19 1/16	29	25	65 1/8	77 1/2	8	3 3/4	3 3/4	16	8	6 11/32	57 11/32	62 7/8	12 1/4	12	6	11	5	3 23/32	23/32	16 1/2	5 3/4	5 1/2	59 1/2	33 13/16	11/16
45-48	48	130 5/8	112 1/8	56	62 5/8	37 3/16	14 9/16	19 11/16	51 7/8	32 9/16	21 7/16	23 5/8	8 3/4	31	21 1/16	31	28	66 1/8	78 1/2	10	5	5	20	8	6 11/32	56 11/16	62 7/8	12 1/4	14	8	13 7/8	7 7/8	3 23/32	23/32	16 1/2	5 3/4	5 1/2	76	44 3/8	11/16
5-48	48	130 5/8	121 1/8	60 1/16	64 3/16	37 3/16	14 9/16	21 3/8	53 9/16	34 1/2	20 15/16	26 1/2	8 3/4	31	21 1/16	31	28	66 1/8	78 1/2	10	5	5	20	9	8 11/32	58 3/8	66 7/8	12 1/4	14 7/8	6 7/8	13 7/8	5 7/8	3 23/32	23/32	19	5 3/4	5 1/2	76	46 1/16	11/16
45-60	60	154 5/8	112 1/8	56	74 5/8	37 3/16	14 9/16	19 11/16	51 7/8	32 9/16	21 7/16	23 5/8	8 3/4	31	21 1/16	31	28	78 1/8	90 1/2	10	5	5	20	8	6 11/32	68 11/16	62 7/8	12 1/4	14	8	13 7/8	7 7/8	3 23/32	23/32	16 1/2	5 3/4	5 1/2	76	44 3/8	11/16
5-60	60	154 5/8	121 1/8	60 1/16	76 3/16	37 3/16	14 9/16	21 3/8	53 9/16	34 1/2	20 15/16	26 1/2	8 3/4	31	21 1/16	31	28	78 1/8	90 1/2	10	5	5	20	9	8 11/32	70 3/8	66 7/8	12 1/4	14 7/8	6 7/8	13 7/8	5 7/8	3 23/32	23/32	19	5 3/4	5 1/2	76	46 1/16	11/16
46-72	72	178	116 3/16	58 1/16	86 7/8	39 1/4	16 9/16	19 11/16	65 13/16	32 9/16	23 1/2	23 5/8	8 3/4	33	23 1/16	33	30	89	101 3/8	12	6	6	24	8	6 11/32	80 11/16	62 7/8	12 1/4	16	10	15 13/16	9 13/16	3 23/32	23/32	16 1/2	5 3/4	5 1/2	102	58 1/16	11/16
56-72	72"	178	125 3/16	62 1/8	88 9/16	39 1/4	16 9/16	21 3/8	67 1/2	34 1/2	23	26 1/2	8 3/4	33	23 1/16	33	30	89	101 3/8	12	6	6	24	9	8 11/32	82 5/8	66 7/8	12 1/4	16 7/8	8 7/8	15 13/16	7 13/16	3 23/32	23/32	19	5 3/4	5 1/2	102	60	11/16
46-90	90	214	116 3/16	58 1/16	104 7/8	39 1/4	16 9/16	19 11/16	65 13/16	32 9/16	23 1/2	23 5/8	8 3/4	33	23 1/16	33	30	107	119 3/8	12	6	6	24	8	6 11/32	98 11/16	62 7/8	12 1/4	16	10	15 13/16	9 13/16	3 23/32	23/32	16 1/2	5 3/4	5 1/2	102	58 1/16	11/16
56-90	90	214	125 3/16	62 1/8	106 9/16	39 1/4	16 9/16	21 3/8	67 1/2	34 1/2	23	26 1/2	8 3/4	33	23 1/16	33	30	107	119 3/8	12	6	6	24	9	8 11/32	100 5/8	66 7/8	12 1/4	16 7/8	8 7/8	15 13/16	7 13/16	3 23/32	23/32	19	5 3/4	5 1/2	102	60	11/16

Fig. 157 (continued)

Fig. 157. Complete specifications for duplex Cincinnati hydromatics. (Courtesy Cincinnati Milling Machine Co., Cincinnati.)

SIZE OF MACHINE	3-24	3-36	34-36	4-36	34-48	4-48	35-48	45-48	5-48
Spindle speeds, number	8	8	8	8	8	8	8	8	8
Standard series, R.P.M. (c)	27-200	27-200	27-200	20-150	27-200	20-150	27-200	20-150	17-127
Low series, R.P.M. (d)	20-150	20-150	20-150	15-113	20-150	15-113	20-150	15-113	13-95
High series, R.P.M. (e)	50-370	50-370	50-370	43-320	50-370	43-320	50-370	43-320	35-260
Note—High and low series furnished only at extra cost.									
Feed per minute, inches, any from	0-40	0-40	0-40	0-40	0-40	0-40	0-30	0-30	0-30
Automatic intermittent feed	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Power quick traverse, rate per minute, in inches	300	300	300	300	300	300	220	220	220
Automatic spindle stop (one-way feed cycle only)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Spindle reverse	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
(f) Automatic lubrication	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
(g) Motor recommended. (See opposite page for motor compartment dimensions)	7½ H.P.	7½ H.P.	7½ H.P.	15 H.P.	7½ H.P.	15 H.P.	7½ H.P.	15 H.P.	20 H.P.
Cutter coolant pump capacity, gallons per minute	20	20	20	20	20	20	20	20	20
Floor space required, inches	78x92	100x92	107x97	105x110	130x97	129x110	132x102	130x113	130x125
Net weight, chain motor drive, exclusive of motor, pounds	10,000	10,300	11,800	15,000	12,800	15,500	13,300	17,500	18,000
Approximate gross weight (export, boxed, lbs.), chain motor drive, exclusive of motor	11,500	11,800	13,800	18,000	15,100	18,500	15,600	20,100	21,500
Size of case, export	96x64x68	96x64x79	106x64x92	111x67x92	114x64x95	114x67x102	124x64x100	124x67x106	124x72x111
Gross weight, domestic, on skids, pounds	11,000	11,300	12,800	17,000	13,900	17,500	14,400	18,600	19,500
Code word, motor drive, one-way cycle	Hymux	Hyief	Hyjox	Hyhat	Hykit	Hybye	Hyvwi	Hyzzu	Hypul

SIZE OF MACHINE	35-60	45-60 (b)	5-60	36-72 (b)	46-72 (b)	56-72 (b)	36-90 (b)	46-90 (b)	56-90 (b)
Spindle speeds, number	8	8	8	8	8	8	8	8	8
Standard series, R.P.M ( )	27-200	20-150	17-127	27-200	20-150	17-127	27-200	20-150	17-127
Low series, R.P.M. (d)	20-150	15-113	13-95	20-150	15-113	13-95	20-150	15-113	13-95
High series, R.P.M. (e)	50-370	43-320	35-260	50-370	43-320	35-260	50-370	43-320	35-260
Note—High and low series furnished only at extra cost.									
Feed per minute, inches, any from	0-30	0-30	0-30	0-30	0-30	0-30	0-30	0-30	0-30
Automatic intermittent feed	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Power quick traverse, rate per minute, in inches	220	220	220	220	220	220	220	220	220
Automatic spindle stop (one-way feed cycle only)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Spindle reverse	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
(f) Automatic lubrication	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
(g) Motor recommended. (See opposite page for motor compartment dimensions)	7½ H.P.	15 H.P.	20 H.P.	7½ H.P.	15 H.P.	20 H.P.	7½ H.P.	15 H.P.	20 H.P.
Cutter coolant pump capacity, gallons per minute	20	20	20	20	20	20	20	20	20
Floor space required, inches	156x102	154x113	154x125	180x106	178x119	178x129	216x106	214x119	214x129
Net weight, chain motor drive, exclusive of motor, pounds	18,000	18,500	19,000	22,500	23,000	23,500	23,500	24,000	24,500
Approximate gross weight (export, boxed), chain motor drive, exclusive of motor, pounds	21,000	21,500	22,000	27,000	27,500	28,000	28,500	29,000	29,500
Size of case, export (See (b) under important notes)	137x64x100	131x43x40 64x76x47 64x76x47	131x43x40 64x76x47 64x76x47	164x64x104	156x72x59 68x70x52 60x70x52	156x72x59 68x70x52 60x70x52	182x64x104	174x72x59 68x70x52 60x70x52	174x72x59 68x70x52 60x70x52
Gross weight, domestic, on skids, pounds	19,500	20,000	20,500	24,500	25,000	25,000	25,500	26,000	26,500
Code word, motor drive, one-way cycle	Hyvav	Hymmo	Hyrea	Hyzko	Hypic	Hysev	Hyzla	Hyaut	Hynty

Fig. 157 (continued)

EQUIPMENT

Two arbor tightening rods, four wrenches, four sets of reversible speed change gears for each head. Overarms provided at extra cost. Dogs supplied for one-way cycle are: 2 feed, 1 quick forward, 1 reverse, and 1 stop.

SPINDLE SPEEDS

(c) Standard Series—27-200 = 27, 35, 49, 63, 86, 111, 155, 200.
(c) Standard Series—20-150 = 20, 28, 37, 48, 63, 83, 110, 150.
(c) Standard Series—17-127 = 17, 23, 31, 40, 53, 69, 92, 127.
(d) Low Series—20-150 = 20, 26, 37, 47, 65, 83, 115, 150.
(d) Low Series—15-113 = 15, 21, 28, 36, 47, 62, 83, 113.

(d) Low Series—13-95 = 13, 17, 23, 30, 39, 52, 69, 95.
(e) High Series—50-370 = 50, 65, 91, 117, 159, 205, 287, 370.
(e) High Series—43-320 = 43, 55, 79, 103, 135, 177, 235, 320.
(e) High Series—35-260 = 35, 47, 63, 82, 106, 141, 186, 260.
High and low series speeds can be supplied at extra cost.
Changes must be made at factory.

When ordering Hydromatics, it is necessary to specify the current available. If A. C. current, we require phase, cycle and voltage; if D. C. current, we require voltage only.

IMPORTANT NOTES

(g) Constant speed motor should be used with a speed not faster than 1800 R.P.M. or slower than 1150 R.P.M. When direct current is available, shunt-wound motors only, can be used. *Motor leads must be on right-hand side of motor when facing pulley end.*

Duplex machine can be widened to obtain increased distance between spindle noses by casting filler blocks to the headstock. These are supplied in increments of 3″ per headstock up to a maximum of 9″ on the No. 3 sizes, 12″ on the No. 4 sizes, and to 18″ on the No. 5 sizes.

Duplex machines are supplied with one-way feed cycle only. Variable feed attachment can be supplied on any machine at extra cost.

Positive stop and delayed trip mechanism for one-way cycle is supplied on special order. The use of the positive stop and delayed trip precludes the use of automatic spindle stop. Positive stop and delayed trip requires use of the Variable Feed Attachment. Positive stop essential for accuracy of trip closer than $\frac{1}{32}$″.

(f) Oil-shot oiling located on side of headstock oils table bearings, chain drive, feed trip mechanism, elevating shaft, and pulley bracket—all other parts automatically lubricated.

(b) The 45-60, 36-72, 36-90, 46-72, 46-90, 56-72 and 56-90 Duplex machines cannot be shipped as a unit inasmuch as the allowable width is 9 ft. It is therefore necessary to remove the left-hand upright and left-hand spindle carrier unit from the assembled machine.

OIL FOR HYDROMATIC FEED UNITS

Oil of following general specifications should be obtained for Hydromatic system:

Fill to high level on gauge when table is in extreme left position. Fill with high-grade light mineral oil. Viscosity 150 seconds Saybolt at 100 degrees Fahrenheit, Vacuum Oil Co. "D.T.E." light turbine oil or an equivalent paraffin base oil. Oil and container must be absolutely clean. Drain and refill reservoir once every four months. On a regular 3-24 unit, approximately 12 gallons are required; on a 4-36, approximately 14 gallons; on a 5-48, approximately 16 gallons. System is filled through regular filling hole in top of oil cover plate. After filling, run table back and forth several times before putting machine into operation. The oil must at all times register between the high and low limit on the inspection glass.

Fig. 157 (concluded)

Fig. 157. Complete specifications for duplex Cincinnati hydromatics. (Courtesy Cincinnati Milling Machine Co., Cincinnati.)

by a 3-HP motor; others are moderately heavy; and some are built to be powered by as much as a 7½-HP motor. A study of the catalogue specifications of a machine will usually reveal for what class of service it is suited. Obviously, a machine should be selected adequate for any particular purpose but not necessarily more rugged than required.

Power presses are rated partly by the extreme forces that they are designed to deliver, in tons. Therefore, a factor in the selection of a power press is the calculation of the force required for the work to be done on it. Formulae, tables, and charts are available in handbooks and reference books for estimating these forces. To illustrate the procedure for stamping operations, the following example is given.

Example 19: A flat punch and die have an action like that depicted in Fig. 158A. As the flat punch progresses through the stock, it meets more and more resistance. The force exerted builds up to a point where the resulting shearing stress exceeds the ultimate strength of the material.

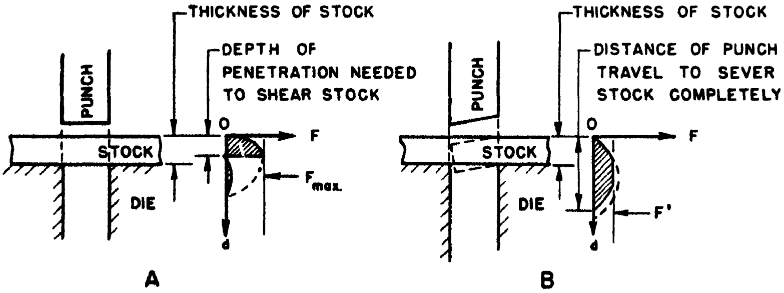

THICKNESS OF STOCK
DEPTH OF PENETRATION NEEDED TO SHEAR STOCK
PUNCH
STOCK
DIE
O
F
F max.
d
A
THICKNESS OF STOCK
DISTANCE OF PUNCH TRAVEL TO SEVER STOCK COMPLETELY
PUNCH
STOCK
DIE
O
F
F'
d
B

Fig. 158. (A) Diagram of the force exerted by a punch without shear.
(B) Diagram of the force exerted by a punch with shear.

Fractures take place almost instantly when the punch has reached the depth of penetration required for the material, and the force falls off to a very small amount. If friction is neglected, the maximum force for penetration is:

$$F = LtS = \pi DtS \tag{69}$$

where

L = total length of cut, in inches,
D = diameter of punch if it is round (or the sum of diameters if several punches are used), in inches,
t = thickness of stock, in inches,
S = shearing strength of material, in pounds per square inch.

Thus, if a 3-in. diameter is to be blanked from a ⅛-in. thick sheet of steel having a shearing strength of 60,000 lb per square inch by a flat punch and die, the maximum force required is

$$F_{\max} = \pi \times 3 \times \tfrac{1}{8} \times 60{,}000 = 70{,}686 \text{ lb} = 35.34 \text{ tons}$$

However, shear is often put on punches or dies by inclining the cutting edges to distribute the load over a longer stroke and reduce the peak of the load. The action then is like that depicted in Fig. 158B. Only part of the punch is fully engaged at any instant, and the force exerted builds up to a smaller amount than for a flat punch. With shear, the penetrating force in pounds can be found from the expression

$$F' = F_{\max} \times t \times \frac{p}{v} \tag{69a}$$

where

p = percentage of penetration into stock needed for shearing, obtainable from tables of material specifications,

v = amount of shear on punch or die, in inches.

Equation (69a) does not apply for punches having shear (v) less than $t \times p$, since it is not logical that F' should exceed $F_{\max}$. An effect similar to shear may be obtained by staggering several punches in one die. Punches and shearing edges properly ground and staggered are assumed.

Thus, if the material in this example must have 25 per cent penetration for shearing and 1/16-in. shear is put on the punch, the maximum force is reduced to

$$F' = 70{,}686 \times \tfrac{1}{8} \times \frac{0.25}{\tfrac{1}{16}} = 35{,}343 \text{ lb} = 17.67 \text{ tons}$$

In the event the die has heavy stripper springs, the load may be somewhat higher. Generally, 10 per cent is considered sufficient for the extra amount.[1]

Problem 46. A piece having a peripheral length of 15 in. is blanked from 0.050-in. thick material having a shearing stress of 40,000 lbs/in.^{2} What maximum force is required for each stroke with a flat punch and die?

Problem 47. The material of Problem 46 requires a penetration of 60 per cent for shearing. If the punch is given a shear of 0.050 in., what maximum force is required?

Problem 48. An elongated hole 2½ in. long has a ½-in. radius at each end and is to be pierced in 20-gage cold-rolled steel of 0.15 C content. A shear of 0.026 in. is to be put on the punch. A stripper is expected to increase the force 10 per cent. What tonnage capacity should the press have?

d. *The power of the machine* determines the rate at which it can do the job or if it can do the job at all. An investigation of power requirements must take into account the basic power consumption of the particular operation and the power losses in the machine.

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[1] Wm. H. Schutt, *Process Engineering*, page 14. New York: McGraw-Hill Book Co., Inc., 1948.

The exact amount of power likely to be needed for any operation is difficult to forecast, but reasonably close estimates of needs can be made. Machine power losses must be estimated. The unit power consumption for many materials and typical cutting and forming operations have been studied. Available data are extensive and can be found in reference and handbooks. To illustrate the use of such data, the following two examples are given.

EXAMPLE 20: In a metal-stamping operation, the energy consumed by the punch penetrating the material is the working distance multiplied by the average force exerted, i.e., the area under the force-distance curve of Fig. 158. Such curves or even average forces are not easy to obtain for specific cases. Consequently, an approximate method is used to find the energy needed for stamping or shearing. The maximum force for a punch without shear is assumed to act over a distance equal to the depth of penetration for shearing the material. Thus:

$$E = F_{\max} \times t \times p \times k \tag{70}$$

where

E = energy for shearing the material (one stroke), in pound inches (or ton inches),
$F_{\max}$ = maximum force exerted by punch without shear, in pounds (or tons),
t = thickness of stock, in inches,
p = percentage of penetration into stock needed for shearing,
k = a factor to allow for energy lost in machine friction, in pushing slugs through die, etc. The amount of extra energy required depends upon the circumstances in each case. For general purposes a factor of 1.16 is advocated.[2]

It can be shown that Eq. (70) is applicable, even if shear is put on the punch or die, but the value used for $F_{\max}$ must still be that which would exist if there were no shear.

The energy to blank a 3-in. diameter piece from the ⅛-in. thick material described in Example 19 is

$$\begin{aligned} E &= 70{,}686 \times \tfrac{1}{8} \times 0.25 \times 1.16 \\ &= 2{,}562.35 \text{ lb-in.} \\ &= 213.53 \text{ lb-ft} \\ &= 1.28 \text{ ton-in.} \end{aligned}$$

Since the energy used for stamping is expended in a short period of time, it must be derived from the inertia of the flywheel. A basic expression for the energy stored in a rotating flywheel with a rim that is massive as compared to the spokes or web is

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[2] *Computations for Sheet Metal Working Operations.* Brooklyn, N. Y.: E. W. Bliss Company.

$$E' = \frac{WV^2}{2g} \tag{71}$$

where

E' = energy in flywheel, in units corresponding to other factors of the expression, in pound-feet,
W = weight of flywheel, in pounds,
V = velocity of point on flywheel in feet per second, at a mean radius r,
= ωr,
ω = angular velocity, in radians per second,
g = acceleration of gravity (32.1 ft/sec²),

The flywheel gives up energy by losing speed. The energy imparted by a change in velocity from V_1 to V_2 is

$$E = \frac{W}{2g}(V_1^2 - V_2^2) \tag{72}$$

For intermittent operation a loss of 20 per cent in speed may be allowed; but for continuous operation a 10 per cent loss is considered the limit, because there is less time for the motor to restore the energy to the flywheel. If $V_2 = 0.8V_1$, which is the condition for a 20 per cent loss in speed, $(V_1^2 - V_2^2) = 0.36V_1^2$. Thus, for intermittent operation, the size and speed of the flywheel must be such that

$$WV^2 = 178.5E \tag{73}$$

or

$$Wr^2N^2 = 2{,}345{,}000E$$

where

r = the mean radius of the flywheel, in inches,
N = rotating speed of flywheel, in r.p.m.,
E = energy, in pound-feet,

For this specific case, where $E = 213.53$ lb-ft,

$$2{,}345{,}000E = 5 \times 10^8$$

A press having a flywheel for which the product Wr^2N^2 is at least 5×10^8 must be selected for this application. A number A2¼ press of one make is rated for 23 tons capacity, which should be sufficient to punch out the piece if ample shear is provided, according to the calculations of Example 19. That press has a 250-lb flywheel, which runs at 130 r.p.m. Its diameter is 25 in., for which a mean radius of 11 in. may be assumed. For such a flywheel:

$$Wr^2N^2 = 250 \times 121 \times 16{,}900 = 5.1 \times 10^8$$

Thus, the A2¼ press has a large enough flywheel for the job if the action is only to be intermittent.

A motor applied to a press must be powerful enough to replenish the energy in the flywheel between strokes. Thus, the motor horsepower is

$$P = \frac{En}{33{,}000} \tag{74}$$

where n = strokes of the press per minute.

If the press for the operation under consideration is to make an average of 50 strokes per minute,

$$P = \frac{213.53 \times 50}{33{,}000} = 0.323 \text{ HP}$$

The A2¼ press selected has a 1 HP motor, which should be ample.

Example 21: The unit power consumption for many kinds of metal cutting operations in horsepower per cubic inch of metal removed per minute is available from reference books and handbooks. That information may be used as a guide in estimating the probable maximum requirements of specific metal cutting operations.

A part of alloy steel having a B.H.N. of 200 is to be milled with a 5-in. diameter milling cutter, having four teeth of cemented carbide. The depth of cut is 0.100 in., the width of cut 4 in., and the feed per tooth 0.010 in. A cutting speed of 500 s.f.p.m. is chosen.

The horsepower at the tool may be found from the relationship[3]

$$P_c = aR^m \tag{75}$$

where

P_c = horsepower at the cutter,

R = rate of stock removal, in cubic inches per minute,

a = horsepower at the cutter when the rate of stock removal is 1 in.^{3}/min,

m = slope of the curve, or exponent for the rate of stock removal, R.

The rate of rotation of the cutter is approximately

$$\frac{4 \times 500}{5} = 400 \text{ r.p.m.}$$

and the unit stock removal is

$$R = 4 \times 0.1 \times 0.010 \times 4 \times 400 = 6.4 \text{ in.}^3\text{/min}$$

For this material[3]

$$m = \tfrac{3}{4} \text{ and } a = 2.00 \text{ average}$$

Therefore, $$P_c = 2 \times 6.4^{3/4} = 8 \text{ HP}$$

If the efficiency of the machine is assumed conservatively to be 80 per cent, the power delivered by the motor must be 10 HP.

"It should be remembered that in long production runs, cutters wear constantly and get dull. This wear . . . will increase the power requirement, at times, as much as 75 per cent. . . . For this reason it is inadvisable in most cases to begin machining a large lot of workpieces with an overload on the machine."[4]

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[3] *A Treatise on Milling and Milling Machines*, Vol. II, page 273. Cincinnati, Ohio: The Cincinnati Milling Machine Co., 1946.

[4] A. O. Schmidt, "Trends in Modern Milling Machines," *The Tool Engineer*, March 1949, Vol. XXII, No. 3, page 17.

On the other hand, it is desirable to work a machine as near to capacity as possible for efficiency. Judgment must be exercised in the choice of a machine on the basis of computed horsepower requirements. One manufacturer[5] makes the following recommendations for rates of power consumption:

"Rated capacity for continuous operation.

"25 per cent over the rated capacity for normal operation.

"50 per cent over the rated capacity for intermittent operation, 5 min maximum period. Minimum idle time, between cuts, should equal 1/5 the cutting time.

"75 per cent over the rated capacity for intermittent operation, 1 min maximum period. Minimum idle time between cuts should equal the cutting time."

Problem 49. A workpiece of medium steel is to be milled with a 12-in. diameter carbide milling cutter having 12 teeth. A surface speed of 350 s.f.p.m. and a feed of 0.012 in., per tooth are to be used. The surface is 8 in. wide. The machine efficiency is taken at 75 per cent. What should be the capacity of the driving motor?

Problem 50. A high-speed steel form relieved cutter 6 in. in diameter must remove S.A.E. 1020 steel of 165 B.H.N. at the rate of 4 in.^{3}/min. The machine efficiency is 80 per cent. What should be the motor capacity?

Problem 51. A 10-in. diameter face mill with 8 cemented-carbide teeth is to be used to mill a 6-in. wide surface of cast iron having a B.H.N. of 190. A 1/4-in. deep cut is necessary. For machine efficiency of 80 per cent, what motor capacity is required?

6. *Distinct advantages offered by one machine* over others that are otherwise suitable for the job. This may be based upon the reputation or performance record of one make and kind of machine as compared with competitors. Generally speaking, good-grade machine tools are well matched, although for some specific purposes one may give superior results, which may be in the form of:

a. *Dependable service.* It is only natural for an engineer to rely on machines that have stood up well for him in the past.

b. *Ease of operation.* Controls are more convenient and require less effort on some machines than on others.

c. *Safety to the operator.*

d. *Consistently accurate results.* It is not unusual for one kind of machine, because of its design or construction, to perform more accurately or stand up better for certain kinds of operations than others. Most designers and machine builders have their own ideas about what parts should be favored in a machine tool and carry them out in proportioning their products.

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[5] *Ibid.*

e. *Better finishes*, because of extra rigidity built into a machine.

7. *The availability of the desired machine or equipment.* If a machine is already in the plant, and only a few pieces are to be made, it is usually more desirable to use it, even though more efficient ones for the service are obtainable, rather than consider getting another. Even for larger quantities it is not always wise to tie up capital in new equipment if the equipment on hand will do nearly as well. In jobbing shops particularly, the best shift must usually be made of available equipment for all kinds of work. In many cases this is the most important consideration, because there is no point in working out an otherwise ideal selection and then finding that the required equipment is not available. In selecting a machine because of its availability care must be exercised that:

a. *The machine is not already overloaded.* If it is already working to capacity, it is not a likely candidate for another job.

b. *The particular machine is the one in the most desirable location* for the process for which it is being considered. If several machines are available, a judicious choice of one located near the other equipment used in a process may save an appreciable amount in handling and moving material.

c. *The machine is in good condition.* A worn-out machine, used as a stand-by, is not a desirable choice. An obsolete machine may prove a decided handicap.

d. *Necessary work handling facilities*, cranes, hoists, or conveyers *are in the neighborhood of the machine.* This may be a major factor for heavy work.

SUMMARY

A process consists of a number of items grouped together into operations, each of which must discharge certain obligations in the most efficient manner under the prevailing circumstances. To determine what form shall be given to each operation, the planner must decide which requirements each is to satisfy. A logical procedure for doing that is to:

1. Classify the items according to typical operations, which are:
   a. Founding operations.

- b. Enterprise protection operations.
- c. Critical manufacturing operations.
- d. Placement operations.
- e. Tie-in operations.
- f. Assembly operations.

(All types are not found in every process.)

2. Divide the items of each class into groups which can be taken care of on general types of equipment or by accepted practices.

3. Form the operations from the items of each group. The number of items that can economically be put into an operation depends in a large part upon the machine selected, on the basis of:

- a. The work to be done.
- b. The workpiece.
- c. The tenure of the operation.
- d. The cost of the project.
- e. The capacity required of the machine.
- f. Distinctive advantages.
- g. Availability.

For simple parts, only a few steps and considerations may be necessary. For complex parts, adherence to the procedure is helpful in simplifying the task.

EXAMPLE 22: An analysis of the operations for making the gear of Fig. 135 will exemplify the procedure for setting up operations. It should be understood that this is only one case. In no single instance, nor even in a few, can the idiosyncracies of all processes be displayed. The application of the principle to each plan calls for the exercise of judgment and a knowledge of the techniques of the particular process.

Except for very small quantities, the gear would be machined from a forging not only from the standpoint of economy but also because the forging provides the means for shaping the grain structure to conform to the lines of the object and imparts the maximum structural strength to the particular design. For the subsequent manufacturing operations the preliminary requirements can be stated as:

1. The critical manufacturing operations must include means for:
   - a. Facing the ends of the hub.
   - b. Drilling and boring the hole.
   - c. Facing both sides of the rim of the gear.
   - d. Turning the outside periphery of the gear.
   - e. Turning the 2-in. diameter of the hub.

Where surfaces must be ground, adequate stock must be left at this stage.

Related surfaces that can logically be machined along with the critical surfaces should be included also in the critical manufacturing operations. In this case, such surfaces are:

f. The $1\frac{3}{4}$-in. diameter on both ends of the hub.
g. Both sides of the web.
h. The $5\frac{3}{16}$-in. inside diameters on both sides of the gear.
i. The $\frac{1}{16}$-in. radii on four edges of rim; the $\frac{1}{4}$-in. radii blending into web; and the $\frac{3}{16}$-in. radius and $\frac{1}{16}$-in. radius at ends of 2-in. diameter.

2. The placement operations must make provision for:

a. Carburizing the surfaces to be case hardened.
b. Reheating the gear for hardening.
c. Quenching the gear while holding it in a die to control distortion.

In addition, some means must be provided for leaving soft the surfaces which are not to be hardened. There are several techniques for doing that. Copper-plating alone should be adequate for the outside hub and web surfaces. This method is not as positive as the one in which sufficient stock to absorb all the case is left to be cut off after carburizing and before hardening. The latter method, which may be combined with copper plating for convenience should be applied to the hole to assure that no hard spots will remain to ruin the broach, an expensive tool. Thus, to meet these requirements and others, the placement operations should also include provision for:

d. Copper-plating surfaces not to be hardened.
e. Deplating.
f. Sandblasting to remove scale.
g. Cleaning and degreasing to prepare parts for heat treatment.

3. The tie-in operations must include means for fulfilling specifications of the finished part, including:

a. Cutting the gear teeth.
b. Finishing the teeth.
c. Lapping or touching up the gear teeth if they are finished (shaved) before heat treatment.
d. Cutting spline.
e. Countersinking ends of hole.
f. Grinding outside of gear, 2-in. diameter, and end faces of hub.
g. Polishing or otherwise finishing after heat treatment all surfaces not ground.

The tie-in operations must also meet requirements of placement operations such as:

h. Qualifying by grinding face of rim and end of hub on the same side for location in quenching die.

i. Removal of excess stock from the hole between carburizing and hardening.

The tie-in operations may also include grinding of the hole to prepare it as a locator, thus:

j. Grinding the hole before heat treatment instead of reaming it to close tolerances as a preliminary locator.

k. Grinding hole after heat treatment to align it with other critical surfaces and prepare it as a final locator.

4. For enterprise protection operations, the requirements to be met include:

a. Inspection of raw materials (forgings).
b. Storage of forgings.
c. Inspection of machined parts before heat treatment to assure proper preparation for placement operations.
d. Inspection of surfaces machined between carburizing and hardening.
e. Inspection after hardening.
f. Washing finished piece.
g. Final inspection.

From the foregoing classification of the requirements to produce the gear of Fig. 135, substantial outline can be given to the necessary operations, although the actual selection of equipment and machines and the final form of the operation depends upon other conditions present in each case. Two critical manufacturing operations are indicated, one for the surfaces of each side. For small or moderate production, turret lathes are appropriate. For quantity production, automatic turret lathes or chucking machines would probably be found most efficient. The preliminary outline of the two critical operations indicates that they shall be:

1. Chuck on long end of forged hub with hardened, serrated jaws and locate against rim.
   Turn outside diameter of the gear.
   Face rim, web, and short end of hub.
   Bore inside of rim and turn outside of short hub.
   Drill and bore the hole.
   Form radii on one side.
   Countersink hole 1/16-in. × 45°.
2. Chuck on turned O.D. and locate against rim.
   Turn two diameters on long end of hub.
   Face end of hub, web, and rim.
   Form radii on one side.
   Countersink hole 1/16-in. × 45°.

The placement operations will include those for plating, deplating, and heat treatment, having a prescribed form similar to that of Fig. 140.

For the tie-in operations, the following considerations will apply:

1. The surfaces ground before heat treatment for location in the quenching die can most reliably be finished together to insure parallelism. These surfaces are the end of the short hub and the rim face on the same side. As they are prepared suitably as locators, in conjunction with the hole, for the gear-cutting operation, they may very well be ground at the same time as the hole. Standard internal grinders can be arranged readily to grind all

three surfaces in one setting. The advantage in accuracy gained by grinding the hole together with these other surfaces makes grinding worth considering in place of reaming the hole for size in the critical manufacturing operations.

2. Cutting of the gear teeth, whether by hobbing or shaping, is a specialized function that, on conventional machines, is performed as a separate operation.

3. Finishing of the gear teeth is likewise a specialized function. Shaving before heat treatment or grinding afterwards may be chosen, depending upon available equipment and quantity requirements.

4. Removal of the excess stock and countersinking of the ends of the hole, occurring between carburizing and hardening, can easily be done together on one machine.

5. After hardening, the hole and face of long end of hub are ground for location. Best results in holding the relationship between these two locating surfaces is secured by grinding them together, which can be conveniently arranged on standard internal grinders.

6. The end of the short hub is best ground by itself on a surface grinder because of the location.

7. The outside of the gear and the end diameter of the hub, because of their difference in size are most conveniently ground separately on standard cylindrical grinding machines. If production requirements are high enough to warrant it, a cylindrical grinder may be arranged to grind these two simultaneously in one operation.

8. Lapping of the hardened gear teeth is a specialized operation performed separately.

9. Cutting the spline is likewise a specialized operation individually performed on specialized equipment. It may be shaped or broached, depending upon equipment available and justified equipment investment.

10. Finishing of the unground surfaces, polishing and burring, requires little equipment. It may be done in one operation or split into several in order to promote specialization.

No attempt so far has been made to specify exactly the sequence that the various operations will assume in the process. That is the next consideration that should be given to them.

Problem 52. Specify the operations to machine the casting of Fig. 5. The production rate is 5,000 per month.

Problem 53. Specify the operations to make 500 a month of the brackets of Fig. 136.

Problem 54. Specify the operations to make 250,000 a year of the valve caps of Fig. 137.

Problem 55. What operations are required to make articulated rods, shown in Fig. 138, (a) if 1,000 a month are required? (b) if 15,000 a month are required?

Problem 56. The universal joint spider of Fig. 139 is to be case hardened and finish ground on the 0.5282–0.5278-in. diameters and 0.879–0.877-in. shoulders. Specify the operations to make (a) 120,000 spiders per year, (b) 1,200,000 spiders per year.

QUESTIONS

1. Name six classes of typical operations.

2. What is meant by "founding operations"?

3. What are "enterprise protection operations"?

4. What are "critical manufacturing operations"?

5. What rules should be followed in setting up critical manufacturing operations?

6. What are "placement operations"?

7. Who often devises the forms of placement operations?

8. What are "tie-in operations"?

9. What principles apply to tie-in operations?

10. What are "assembly operations"?

11. What significance is there to classifying requirements according to typical operations?

12. What circumstances make it possible to break down the items in a class of typical operations into special groups?

13. What economic considerations enter into the allotment of work to an operation?

14. Why must machine selection be considered in assigning work to an operation?

15. What are the principal considerations in the selection of a machine?

16. How does the nature of the work to be done enter into the choice of a machine?

17. How does the nature of the workpiece affect the choice of a machine?

18. What influence does the expected tenure of an operation have upon the selection of a machine?

19. What costs should be considered in choosing a machine tool?

20. What must be considered in regard to the capacity of a machine tool?

21. Are range, ruggedness, and power always the same for the same classes of machine tools? Explain.

22. What are some of the criteria of capacity of power presses?

23. In general, how is the power needed for a metal-cutting operation estimated?

24. What distinct advantages may be offered by one make or kind of machine tools over others?

25. When may the availability of a machine tool be important?

26. What precautions must be taken in selecting a machine tool because of its availability?

27. Describe a logical procedure of allocating the requirements of a job to efficient operations. Is the full procedure always necessary?

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12 DETERMINING THE SEQUENCE OF OPERATIONS OF A PROCESS

The general procedure

The first step in laying out a process has been shown to be that of finding the requirements. The second step is to organize the requirements into operations. The third step is then to find the proper sequence of the operations. That can be done by building the process in a manner similar to putting together a jigsaw puzzle, using the operations as the pieces. First, the terminal points are found, then to them are fitted the operations that obviously adjoin. Between them, the other operations fall into natural positions.

The terminal points

In the first step of process planning, the requirements are found from blueprints and other specifications. They evidently prescribe the end point of the process. Their satisfaction is to be proven by the final inspection operation at the end of the process. Also, the form of the raw material must be ascertained. That is the start of the process. If these two conditions are set down, as indicated in Fig. 159A, the terminal points of the process are defined.

The beginning of the process

Before any time and money are expended for working materials, they should be checked against specifications. Also, a bank of materials is normally accumulated so that once production is started, it will not lose momentum from lack of material. Obviously, then, the primary concern after procurement of the workpiece from the founding process is to subject it to appropriate enterprise-protection operations. These are represented by the second insertion of Fig. 159B.

The purpose of the initial manufacturing operations is to establish the critical areas and provide locating surfaces for subsequent work. Therefore, the critical operations must be performed as early as possible in the conversion sequence. Their insertion, the third, is shown also in Fig. 159B.

The placement operations

It is now evident that the placement operations that have been determined must appear between the critical operations and the end of the process. Outside of their relationship to each other, which is usually inherent in their make-up, their exact position is not yet important. Gaps may be left in the plan to receive the tie-in operations needed for the rest of the process. The situation as it now stands is shown by Fig. 159C. If no placement operations are needed, obviously this step is omitted.

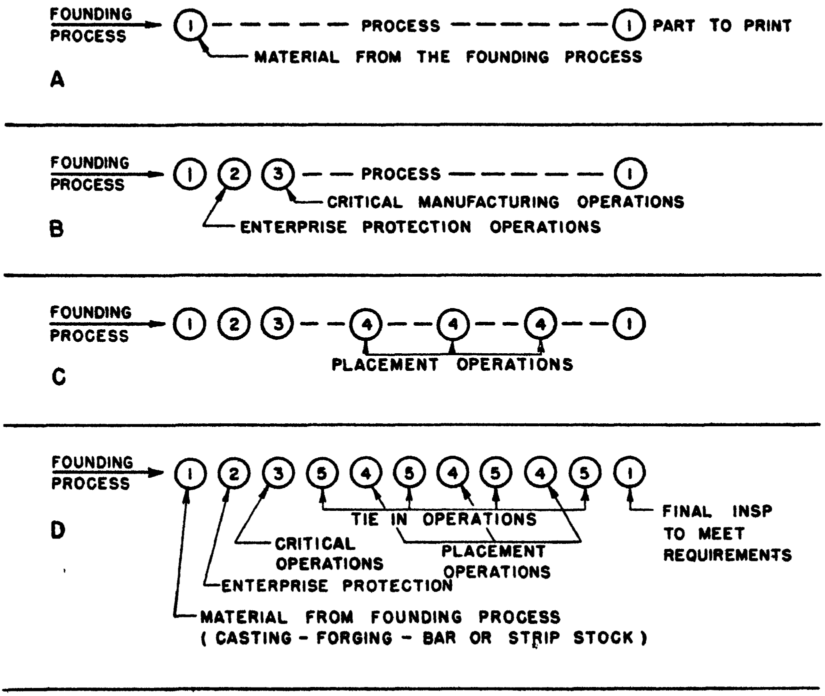


Fig. 159. (A) First step in setting up the sequence of operations. (B) Second step. (C) Third step. (D) Completed sequence of operations.

Completing the plan

Tie-in operations are essentially preparatory operations. Some serve to condition the workpiece for treatment in placement operations; others may adapt the product to conform to the final requirements after it comes from critical manufacturing or placement operations. The general position of a tie-in operation is usually indicated by the purpose for which it is intended. For example, a tie-in operation preparatory to a placement operation should naturally precede it. Thus, the arrangement of the tie-in operation usually serves to fill in the plan of the process as shown in Fig. 159D.

Not infrequently, several tie-in operations may be allotted to a given space within the process plan. Their arrangement within the space in relation to one another is usually a matter of convenience. It may, for instance, be desirable to arrange them to conform to the positions of the machines in the shop. Again, it may be convenient to place them with respect to each other to favor the particular techniques employed. As an example, two tie-in operations may consist of each drilling one of two intersecting holes. If one hole is large in diameter and the other small, it is proper to drill the large one first, so as not to throw the burr into the smaller hole where it is less accessible.

As a final stage in filling out the steps of the process plan the remaining enterprise protection operations may be entered in appropriate positions.

EXAMPLE 23: Figure 160 shows the order in which the operations for making the starter gear of Fig. 135 are considered to reach a logical sequence for the entire process. Actually, there would be no need to enter the operations in separate columns. They would normally be written on the route sheets with ample spaces between them for filling in those remaining. They are charted in Fig. 160 to emphasize the stages of the thought process employed.

As the first step, the known initial conditions of the preparation or procurement of the forging, inspection, storage of the forging, and final inspection are listed at the extremities of the as yet otherwise unknown sequence.

Next, the critical manufacturing operations that have been outlined in Example 22 can be set down as beginning the machining phase of the process. After that, the placement operations of carburizing and hardening, in the third column, can be placed in the interval to allow adequate space for insertion of the remaining operations.

As shown in the fourth column, the tie-in operations are arranged and

Oper. No.	Initial Conditions	Critical Manufacturing Operations	Placement Operations	Tie In Operations	Enterprise Protection Operations
1	Preparation or procurement of forging.				
2	Inspection and storage of forging.				Inspection and storage of forging.
3		Chuck on long hub and locate against rim face. Turn O.D. of gear and short hub. Face rim, web, and short hub end. Bore inside of rim. Drill and bore hole. Form radii. Countersink hole.			
4		Chuck on gear O.D. and locate against faced side of rim. Turn 2 diams. on long hub. Face hub,web,and rim. Bore inside of rim. Form radii and countersink hole.			
5				Chuck on gear O.D. and locate against long hub end.Grind short hub end and rim grind hole.	
6				Locate in I.D. and against rim. Cut gear teeth.	
7				Locate in I.D. and against rim. Shave gear teeth.	
8			Degrease.		
9					Inspect semi-finished piece.
10			Copper plate I.D. 1-3/4 diams. of hub and web.		

11			Carburize.		
12			Clean off carbon.		
13				Locate from teeth and against rim on short hub side. Bore and ream I.D. Countersink both ends.	
14					Inspect.
15			Heat and quench to harden.		
16			Temper.		
17			Deplate & shot blast.		
18					Check runout.
19				Locate in I.D. and against rim face. Lap teeth.	
20				Locate from gear teeth and against rim. Grind I.D. Grind end of long hub.	
21				Locate in I.D. and against end of long hub. Grind end of short hub.	
22				Locate in I.D. Grind O.D.	
23				Locate in I.D. Grind long hub O.D.	
24				Locate in I.D. and against long hub end. Broach spline	
25				Polish unground surfaces. Burr and break edges.	
26					Wash.
27	Final inspection.				Final inspection.

Fig. 160. Sequence of operations required to manufacture the starter gear in Fig. 135.

inserted as appropriate. To complete the process, the remaining enterprise protection operations are entered.

Problem 57. Problem 52 calls for the operations needed to machine the casting of Fig. 5 for a production rate of 5,000 pieces per month. Arrange the operations in proper sequence.

Problem 58. Problem 53 calls for the operations to make 500 a month of the brackets of Fig. 136. Arrange the operations in proper sequence.

Problem 59. Solve Problem 54 to find the operations to make 250,000 a year of the valve caps of Fig. 137, then arrange the operations in proper sequence.

Problem 60. Set down in order the operations to make articulated rods, shown in Fig. 138. The operations are found from the solution of Problem 55.

Problem 61. Arrange the order for the operations for making the spider of Fig. 139 in the manner specified in Problem 56.

QUESTIONS

1. Outline the general procedure for determining the sequence of operations of a process.
2. What are the terminal points of any process?
3. Where should the critical operations come in a process plan?
4. What disposition can be made of the placement operations?
5. Where do the tie-in operations fall into the pattern of a process?

13 PRINCIPLES OF LOCATING

The purpose of workpiece location

In interchangeable manufacture, tools and machines are arranged to carry out definite routines. For consistent results, all workpieces must be presented to the tools in an operation in as nearly the same position as possible. To fulfill this purpose, means must be provided to locate enough surfaces on each object to give it a fully defined placement to which it can be held securely.

Common surfaces have the forms of planes, cylinders, and cones. Sometimes special types of surfaces are found. The surfaces occur in many arrangements. A block may be made up of perpendicular planes; a shaft may have one or more cylindrical surfaces in its length, bounded by planes, with conical centers or round holes in the ends; and a gear may have inside and outside cylindrical surfaces, planes, and involute surfaces. To cope with the many possibilities, many locating means have been devised, but the key to all of them is found in the principles of locating.

The requirements for location

Confinement alone does not insure location. For instance, a piece may be gripped in a chuck with one end extending into the hole in the chuck body, but backed against no support. If its front end has not been set to a stop, the piece cannot be said to be located, although it is held securely. If the piece is removed and another one put in its place, there is no way of setting the second in the same position as the first. Thus, the first requirement for location is that there be a suitable number of points to position each piece of a series in as many co-ordinates of space as the operation requires. The choice of locating points must take into consideration:

1. The six possible degrees of freedom and the criteria of their restrictions.

2. The relative merits of available points for location.
3. The condition of the locating surfaces.
4. The shape of the part.
5. The surfaces to which registration is required.

The test of a locating device is how well it satisfies these considerations for any particular application. Fundamental locating means will be analyzed in this respect.

CONSIDERATIONS IN THE CHOICE OF LOCATING POINTS

The six degrees of freedom

A free body may move in any direction, like *Oc* of Fig. 161. If three arbitrary axes are selected, any movement, *Oc*, can be realized by three equivalent movements, *Oa*, *ab*, and *bc*, in the co-ordinate directions. Restriction of movement in three axial directions prevents linear motion in any direction.

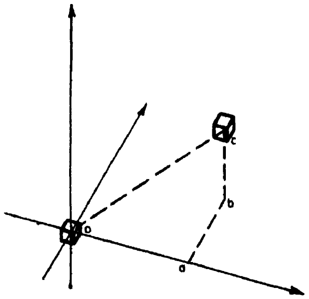


Fig. 161. Movement in any direction is equivalent to movements in three co-ordinate directions.

A free body may also rotate, independent of or without any directional movement. A position reached by an object by rotation in any manner may be arrived at by suitable rotations about three perpendicular axes. This may be illustrated by the punch press frame that has been placed on a boring machine table in the position shown in Fig. 162A. It is to be placed on its base with the crank bores in line with the machine spindle. This may be accomplished by three rotations, each about one of three axes in the following manner. The first is rotation about a horizontal axis perpendicular to the axis of the machine spindle, to reach the position shown at *B*. Next the casting is revolved about an axis parallel to the spindle to place its base upon the table, as shown in *C*. Then a rotation about the vertical axis puts the bores in the desired position, like in *D*. That linear movements may accompany some of the rotations is incidental, as the same rotations could obviously be made if the frame were a free body in space. Also, if no rotation were permitted about the co-ordinate axes, rotation about any axis would not be possible.

Careful studies have shown that any possible change in the position of a body can be duplicated by not more than six elementary movements, three translations and three rotations with respect to three co-ordinate axes. Six may not always be required, but no more than six are ever absolutely necessary. Perfect freedom demands that all six movements be permissible. The lack of any one of the motions means some loss of freedom. Prevention of all six is essential for complete confinement.

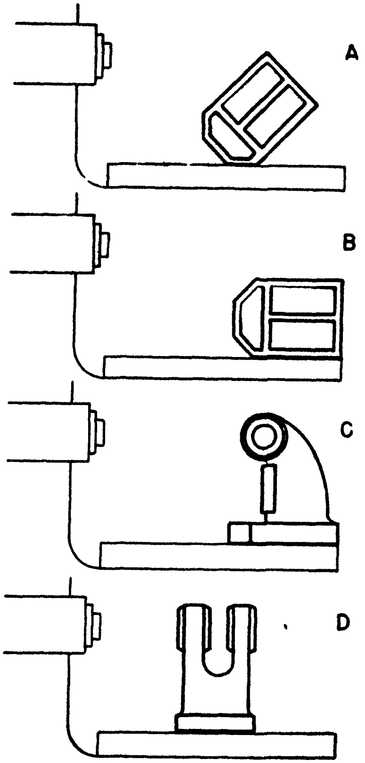
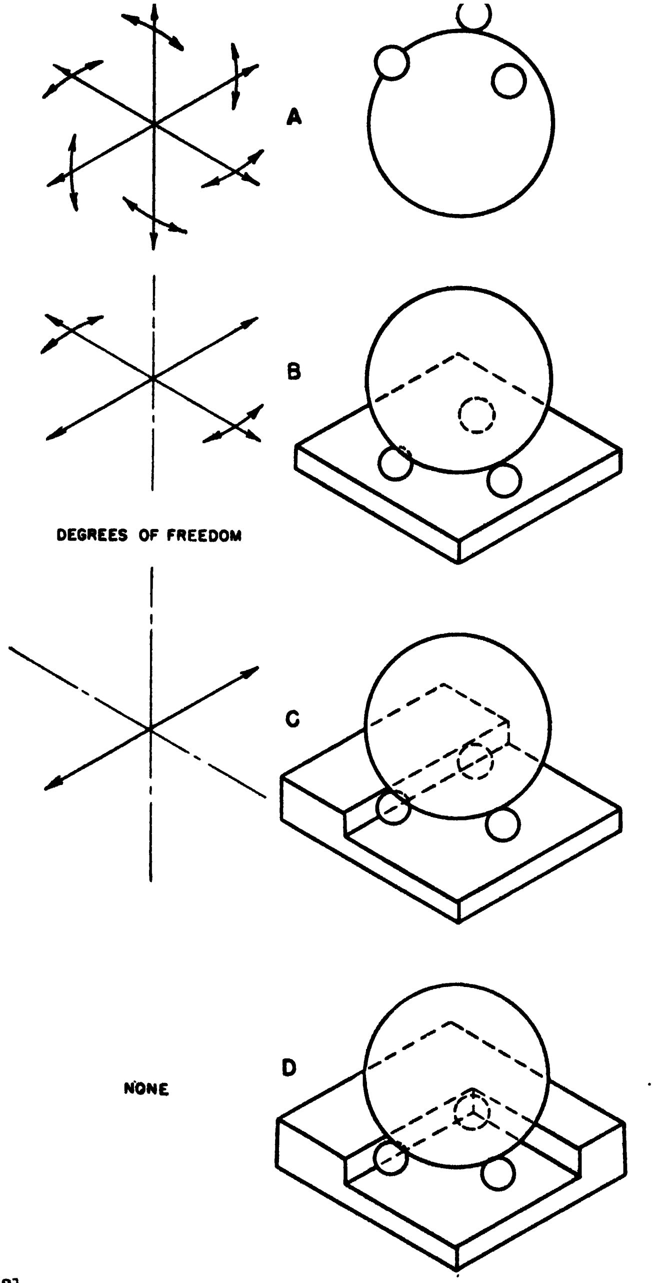


Fig. 162. A punch press frame aligned with spindle of boring machine by three rotations about coordinate axes. (A) The original position of the frame on the boring machine table. (B) The position of the frame after it has been rotated about an axis perpendicular to the machine spindle axis. (C) The position of the frame after a second rotation, about a horizontal axis parallel to the machine spindle axis. (D) The position of the frame, with its crankshaft holes in line with the machine spindle, after the third rotation, about a vertical axis.

Restriction of freedom

Location is established when a suitable number of points on an object are held to prevent any possible motion. Consider a ball free in space, like Fig. 163A, and having all six degrees of freedom. For convenience three legs or knobs are attached. If one of the legs is brought in contact with a horizontal surface and held against it, translation is possible horizontally, but not vertically. At least some rotation is possible in any direction around the contact point. Now, if two and then three legs are brought in contact with the same surface and held there, like in Fig. 163B, two and then three degrees of freedom are eliminated. Only sliding along the horizontal surface and rotation around a vertical axis remain. If in addition a vertical



[Fig. 163]

surface is introduced and one of the legs is held in contact with it (the three still being maintained in contact with the horizontal surface), one horizontal movement is removed. Then, two legs in contact with the same vertical surface, like in *C*, eliminate the final rotation and only a single motion, horizontal sliding, remains. Finally, if one leg is held against two vertical planes, like in *D*, and the other legs continue to contact the surfaces previously described, all movements are precluded and complete location is established.

As has just been illustrated, each point of location eliminates one degree of freedom, up to six points that are necessary to withhold all freedom. More locating points serve no purpose and, as will be shown, may be detrimental.

Proper placement of locating points

The principle which defines the most suitable points for location, of all that may be chosen, was stated by Clark Maxwell in 1876:

"If one of the bearings (by which a three-legged part is located) were removed, the direction in which the corresponding point of the instrument would be left free to move by other bearings must be as nearly as possible normal to the tangent plane at the bearing."

The meaning of this quotation can be explained by reference to Fig. 163D, which depicts a satisfactory condition of location. The tangent planes at the points of contact are the bearings. If one of the legs is moved away from a point of contact, without change in the other points of contact, movement must take place in a direction perpendicular to the plane from which the disconnection is made. For instance, if one of two balls is raised from the horizontal surface, it can only rise vertically as long as it maintains contact with the vertical surface and the other two legs continue to touch as before. The outside leg may slide, and the large ball may move and turn.

As Fig. 163 indicates, the most satisfactory locating points are those in mutually perpendicular planes. Other arrangements are possible, but not as desirable. For instance, three points instead of

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Fig. 163. An illustration of how locating points eliminate freedom of motion. (A) A ball unconfined in space has six possible degrees of freedom. (B) The three small balls, as legs, are held in contact with a horizontal surface, and three degrees of freedom are lost. (C) If two small balls are also held against a vertical surface, five degrees of freedom are lost. (D) If one ball is also held against another vertical surface, perpendicular to the other, all freedom is removed.

being in one plane may lie in two or three parallel planes; also, a plane containing one or more locating points may be oblique to one or both of its companion planes. It will be found that any such displacements are prone to increase locating errors.

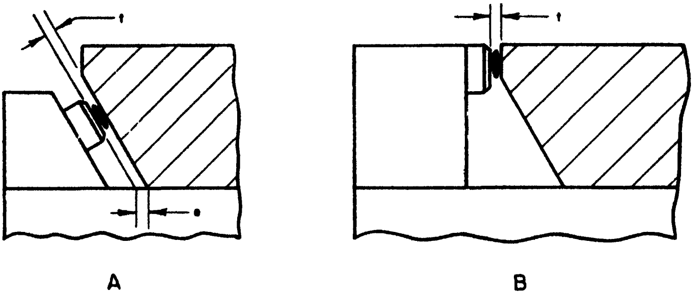

Fig. 164. How normal errors are increased by location taken from other than a vertical plane. A wedging action also results.

Figure 164 illustrates two disadvantages of locating from other than perpendicular planes. At *A*, location is taken on an inclined plane, with a consequent wedging action that tends to lift the piece. Between the locating button and the workpiece is a particle of thickness *t*. The horizontal error from it is *e*, which is greater than the direct error *t* introduced in arrangement *B*.

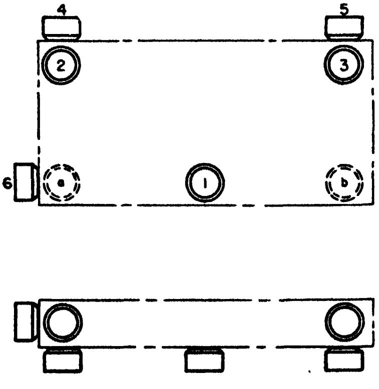

Fig. 165. The 3–2–1 principle of location applied to a piece with rectangular sides.

The 3–2–1 principle of location is the practical summation of the theory of location. It may be stated in this manner: *To locate a piece fully, place and hold it against three points in a base plane, two points in a vertical plane, and one point in a plane square with the first two.* Suitable surfaces may serve as the points.

This principle is most readily illustrated by the location of a piece with rectangular sides, as sketched in Fig. 165. The piece is first placed on points 1, 2, and 3, preferably on its largest face for stability. When held against these points, it is prevented from tilting about any horizontal axis and from moving up or down. Then it is brought against the two locators 4 and 5 in a plane perpendicular to the base, which eliminates two more freedoms. Finally, positive contact with locator number 6 completes confinement.

Because of its name, the principle is easy to remember and apply to checking the sufficiency of locating means. It calls for three points in one plane, two in another, and one in a third and urges that those planes be square with each other and that the points be spaced as far apart as possible.

The condition of locating surfaces

The condition of locating surfaces on a workpiece must be considered in choosing the form of locator. There are three general classes of workpiece surfaces. They are:

1. Finished surfaces that have dependable geometric truth and linear tolerances.
2. Semi-finished surfaces that have been machined, but are subject to appreciable deviations from truth.
3. Rough surfaces which are unmachined and show wide variations.

Finished faces of limited sizes may be placed against fully contacting surfaces. That is, they may be located against planes, instead of on the equivalents of separate points. Thus, in Fig. 165, a plate encompassing the entire base of the block might well be used instead of the buttons *1*, *2*, and *3*. Where buttons are used as base plane locators against a finished surface, there are good reasons to use four instead of three. This is represented in Fig. 165 by buttons *a*, *b*, *2*, and *3* instead of just *1*, *2*, and *3*. For very large finished surfaces, four or more pads may serve as the base plane.

More than three points in a plane do not improve location, but may promote stability and give extra support. An analogy is found in the comparison between a four-legged chair and a three-legged stool. The chair is much less prone to tip on a level floor, but will rock on an irregular surface whereas the stool will take a sure stance on any footing. Similarly, if the four buttons *a*, *b*, *2*, and *3* in Fig. 165 are used to locate a finished surface, it is more difficult to tip the piece than if the three points *1*, *2*, and *3* are used. A stray chip on one button causes the piece to rock on the four-button support and gives warning of its presence, but no sign of it is shown in the way the piece settles on three supports.

Although an excess of locating points may have advantages, it also has disadvantages. With four buttons in one plane, for instance, a noticeable unevenness occurs if one of the buttons, because of wear or faulty construction, does not lie in the plane determined by the other three. If a piece is clamped firmly on to such locators, it may warp; if not secured enough, it may shift under cut.

A rough surface on more than three points in a base plane is like a chair on an uneven floor. More than the minimum number of points in any plane give rise to complications in locating rough surfaces, even sometimes in locating semi-finished surfaces. A continuous surface in contact with a rough piece, like Fig. 166A, presents the possibility of contact at a large number of spots. Only the high spots of the rough surface are brought to bear. The piece is registered only from the extreme projections, and the likelihood of rocking and shifting is obviously increased. A relieved locator, like Fig. 166B, offers means of getting closer to the average plane of the rough surface and holding the piece in a stable position. This same idea applies, of course, whether the plane is one having 1, 2, or 3 locating points. The specific points for locating the rough surfaces of a casting may be qualified by pads, as shown in Fig. 122.

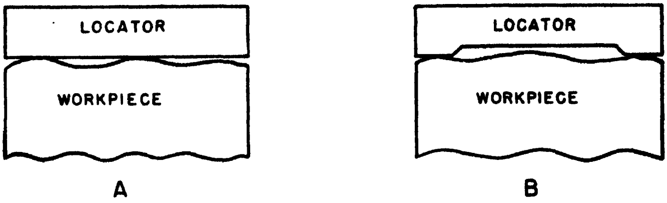

Fig. 166. A relieved locator for a rough surface.

The principle of least points. These examples illustrate a principle. No more points than necessary should be used to secure location in any one plane. The 3–2–1 principle prescribes the necessary minimum. More can be used, and commonly are, for finished surfaces. However, whenever more are used, the extra ones should only be inserted because they serve a useful purpose, and care must be taken that they do not impair the location. Where extra supports are needed but interfere with location, if fixed, they should be made adjustable.

The principle of extreme positions. It should be noticed that in Figs. 165 and 166 the contact points are at the extremities of the surfaces to be located. That conforms to the principle that locating points should be chosen as far apart as possible on any one surface. This is desirable because, for a certain displacement of any point with respect to another, the resulting misalignment decreases as the distance between the points is increased.

The shape of the part

The shape of a workpiece determines to a large extent the kind of locator suited for it. As will be shown, each type of locator takes care of certain shapes most conveniently.

The surfaces requiring registration

A basic principle of metal processing is that a part should be located in an operation from areas most directly connected to the surface or surfaces treated in the operation. This principle is carried out in the use of critical areas as locators for other surfaces throughout a process.

This principle may be illustrated by a simple case. A surface A is to be finished to a dimension a, with a tolerance t_1, from a surface B. If location is taken from surface B, the tool to finish A will have to perform on each piece only within the tolerance t_1. On the other hand, if another surface C is used for locating, it must be expected to vary in its position from B by a tolerance t_2, and the tool must finish A with respect to the surface C from which it is set to a tolerance t_3. The variation of t_3 must be smaller than t_1, since $t_2 + t_3$ must not exceed t_1 if all workpieces are to have the dimension a within limits specified. Thus, if C is used as the locating surface more accurate performance is required than if B is the locating surface.

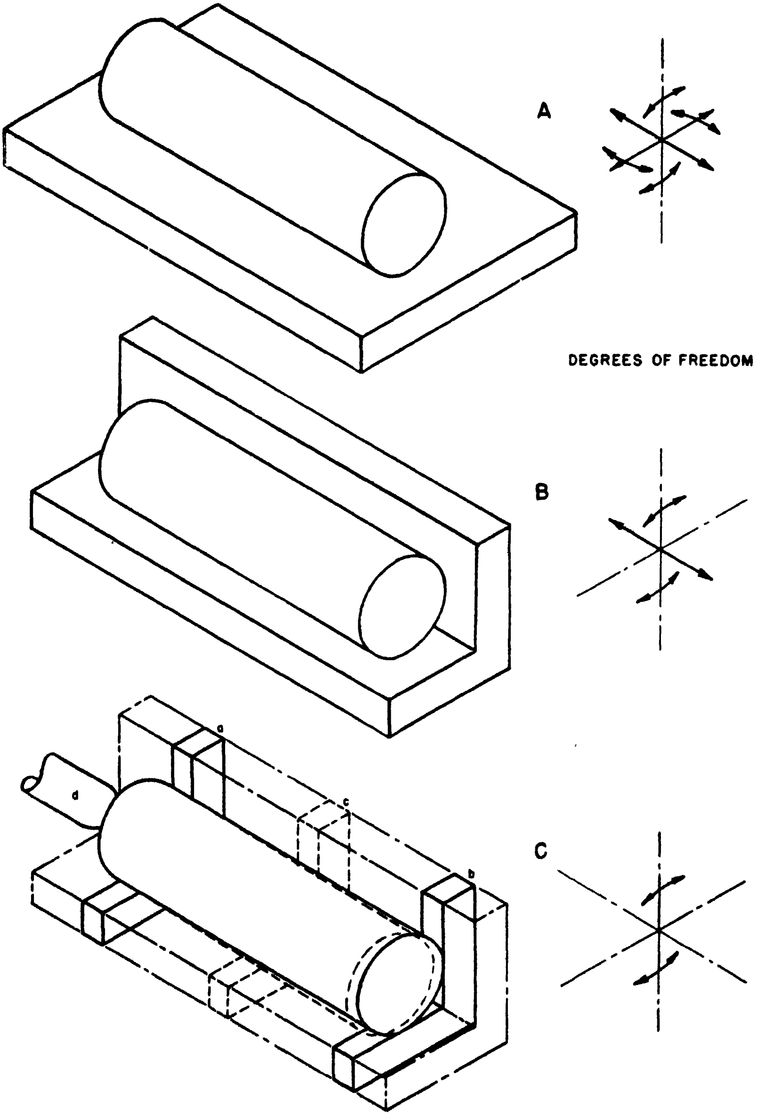

Fig. 167. Locating a cylinder in a V.

FUNDAMENTAL LOCATING ARRANGEMENTS

V-locators

A true cylinder lying on a plane, like in Fig. 167, loses two degrees of freedom. It may remain on the plane and still move in any horizontal direction and rotate about its own axis and a vertical axis. If in addition the cylinder is brought against a vertical plane, like in Fig. 167B, four degrees of freedom are eliminated.

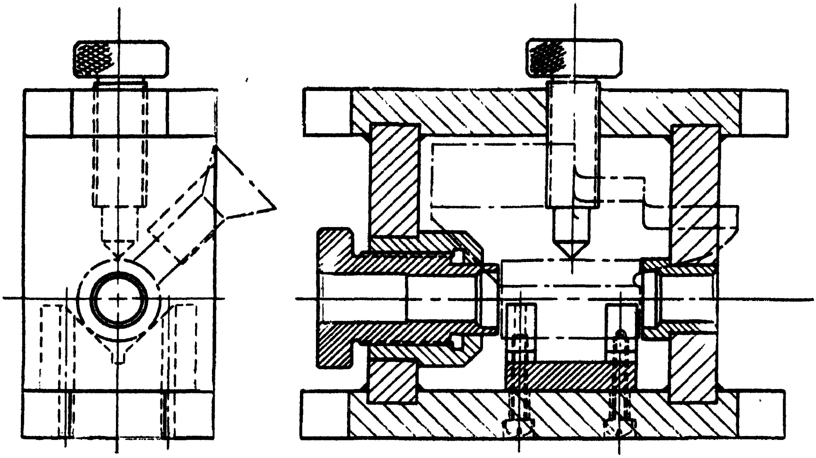

Fig. 168. A jig of welded construction for drilling and reaming a ⅝-in. diameter hole axially through the body of a casting. The barrel or body is located in the double-V block. Drill thrust is taken against the head of the fixed reamer bushing; reamer pressure by the screw bushing. Drill torque is counteracted by having the flange of the piece secured in a slot in the body.

The pieces are made occasionally in small quantities. The jig legs are unhardened extensions of the machine steel body. Screw clamping, although slow, is justified by the low production.

For a cylinder located from perpendicular planes, like Fig. 167B, only two points are effective in each plane. Consequently, two V's, like *a* and *b* of view *C*, near the ends of the cylinder are fully as effective. In fact, they are preferable if the cylinder is not entirely true. On continuous planes, a rough bar is likely to make contact at points between its ends and be subject to rocking. A superfluous V, like the one shown by dotted lines at *c* in Fig. 167C, may cause the same sort of instability if either the piece is not straight or the locators are not exactly in line. A rough body aligned in two V-locators is shown in Fig. 168.

An end stop, like *d* of Fig. 167 or the fixed bushing of Fig. 168,

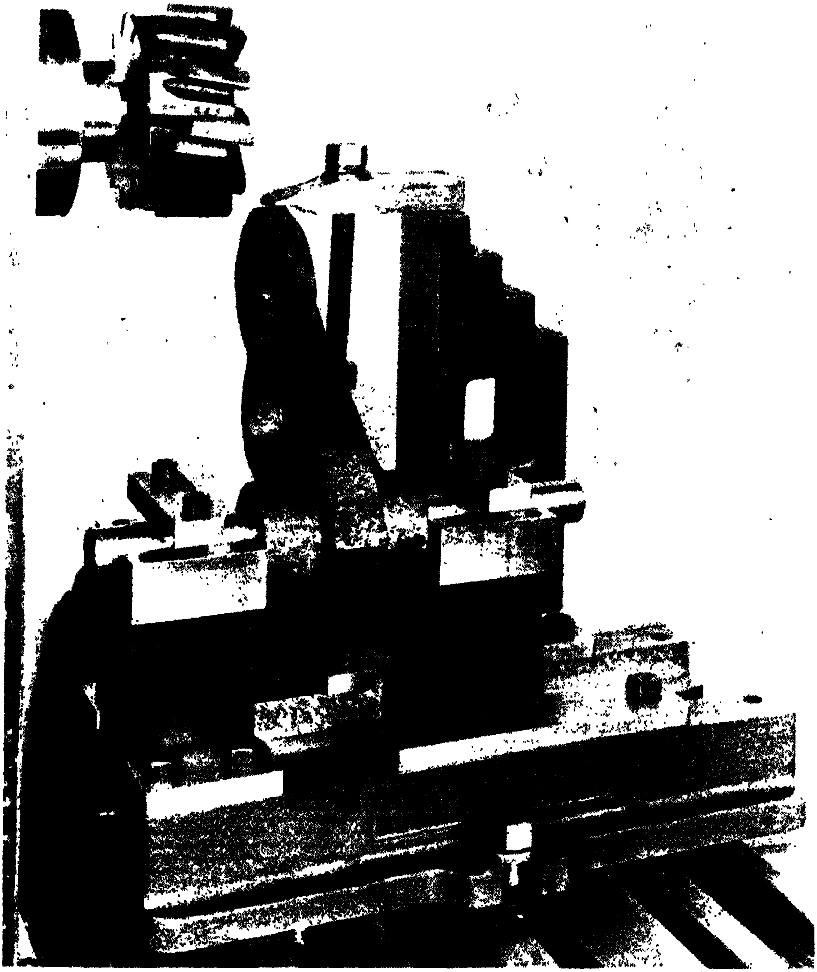

Fig. 169. A setup for moderate quantities. The flange of the casting is to be faced square with the axis of the hole which is mounted on an arbor placed in a standard V-block fixture. (Courtesy Hartford Special Machinery Co., Hartford, Conn.)

eliminates a fifth degree of freedom. There still remains rotation about the axis of the cylinders. This may be impeded by friction if the piece is pressed against the V's by a clamping force, but that does not constitute true location as it does not provide means for placing each piece in a definite angular position. However, unless there is some mark, projection, or hole on the surface of the cylinder to which reference is desired, there is no need for angular disposition. The flange of the piece of Fig. 168 is inserted in the slot in the jig body, not for angular location, which is irrelevant to drilling the hole in the center of the body, but to take the drilling torque. The primary object of locating a round body in V-blocks is to place its axis in a definite position. This is all that is necessary for initial cross drilling, drilling or turning concentric with the axis, or facing. In Fig. 169, a standard type of V-block fixture locates a mandrel fitted in the hole of a casting so that a flange can be faced square with the axis of the hole.

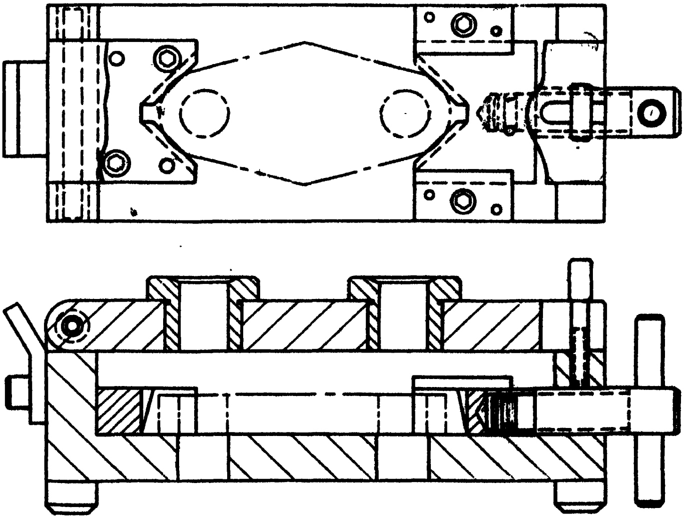

Fig. 170. A drill jig for a small connecting rod. The swinging leaf carries the drill bushings and is guided at both ends in slots in the jig body. The workpiece is located between V-blocks, one fixed and the other movable. The contact faces of the V's are tapered to assist in holding the workpiece down.

A single, narrow V provides two points for location. The equivalent of three points in a base plane and a locating point on a radius are necessary to supplement a single V for complete confinement of all six degrees of freedom. A piece located in this manner is shown in Fig. 170. One cylindrical end is centralized by the fixed V-block. A finished face of the piece rests on a plane, the equivalent of three points, and radial location is obtained from the sliding V-block.

The connecting rod in the jig of Fig. 44 is to have the wrist-pin hole drilled at a certain distance from the center of the crankshaft-bearing boss. The V-locator with sloping faces, on the outboard support of the jig locates the center of that large boss. Supports under the bosses at the ends of the rod provide location in a base plane. The bushing plate carries a suspended V for radial location of the rod and for centralizing the wrist-pin boss with the drill bushing. The bushing plate with its attached V is brought down for clamping. The drill torque holds the outer end of the rod in the outer V.

The two preceding examples show an extra locating point for each part, which may not seem in keeping with the principle of locating already laid down, that the equivalents of six points locate an object with respect to the basic six degrees of freedom. Each of the two parts rests on a base plane that provides three points for location. Also, the fixed V-block for each part supplies two more points. The movable V-block in each jig also has two points of contact, making a total of seven. However, each movable V-block actually serves to locate only one point, the center of the section each encompasses. In this capacity, a V-block performs the function of a "centralizer." That function will be described in more detail later.

The bearing cap of Fig. 171 is located in accordance with the principle of V-block location, although the arrangement of the details is somewhat different from that shown in the other examples. The workpiece is pressed into the two fixed V's that serve to centralize the two bosses through which the holes are drilled. The bushing plate is brought down to do the clamping and furnish the equivalent of the base plane. The movable bushing plate may seem an infraction of the rule that principal locators should be fixed. However, the plate also carries the bushings that guide the drills and is fixed with reference to them. Also, with respect to the V-locators the plate is quite stable since the rugged body of the jig maintains accurate alignment. A high degree of dependability can be built into such standard jig bodies at a reasonable cost, since they are produced in quantities.

Another application of a V-block locator and centralizer is shown in Fig. 231. In that fixture the V-block supports and centralizes the round shank of the piece. The body of the workpiece rests upon

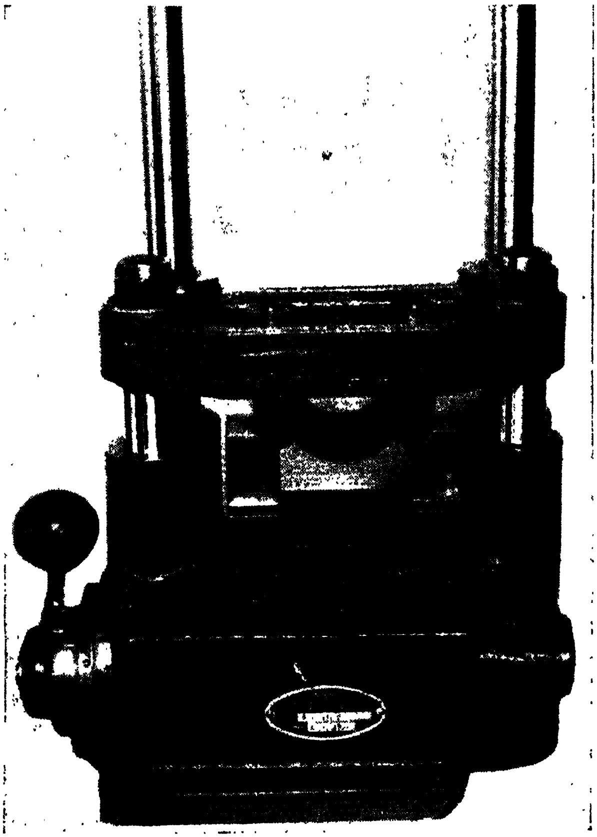

Fig. 171. A universal jig body adapted for drilling holes in main bearing caps on a rotary drill press. The bushing plate of the jig furnishes the surface for locating the parting face of the main bearing cap. The tapered V-blocks locate and centralize the bosses through which holes are drilled. The piece is clamped between the V's and bushing plate, when the latter is lowered.

The jig is equipped with guide posts to align a drill head. (Courtesy Swartz Tool Products Co., Detroit.)

two pads and is pressed against a vertical pad. A stop is provided at the end of the shank.

Proportions of V-locators. The angle between V-locating surfaces influences the positions taken by circular sections of various diameters. In Fig. 172 a V with an included angle 2α locates a circle of radius r_1 with its center at A. A second circle of radius r_2 has its center at B. The distance between A and B is c. By similar triangles,

$$\frac{r_1}{OA} = \frac{r_2}{OA + c}$$

but

$$OA = r_1 \operatorname{cosec} \alpha$$

and

$$c = \operatorname{cosec} \alpha\,(r_2 - r_1)$$

$$= \frac{\operatorname{cosec} \alpha}{2}(D_2 - D_1) \qquad (76)$$

where D_2 is the diameter of the larger circle of radius r_2 and D_1 is the diameter of circle of radius r_1.

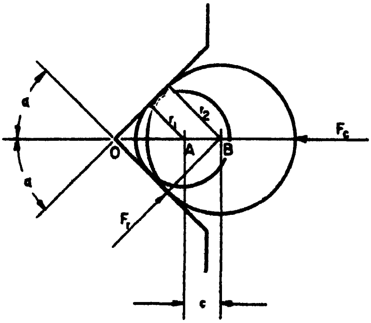

Fig. 172. Two different sizes of round pieces in a V.

The meaning of Eq. 76 is that the distance between the positions taken by the axes of two particular diameters in a V varies as one-half the cosecant of half the included angle of the V. The curve for cosec $\alpha/2$ from 0 to 90° is included in Fig. 173. The least displacement occurs when $\alpha = 90°$, where cosec $\alpha/2 = 0.5$ But as α approaches 90° (a total included angle in the V of 180°) there is less inclination for a piece to seat positively in the V and more difficulty in retaining it. Judgment usually dictates that the best compromise between displacement and security is found at an angle α of 45° (a 90° included angle).

Problem 62. For a constant clamping force F_c acting on a constant diameter D_2 through the center of the V of Fig. 172 show how the vertical and horizontal components of F_R exerted by each side of the V on the piece vary with α. What does this indicate about the retentiveness of the V as its included angle is increased?

A rough piece may have a bump on its surface, which comes in contact with one side of a V-locator, like in Fig. 174A, or a round piece may be displaced by a chip, like in Fig. 174B. What influence does the angle of the V have, if any, upon the effects of these disturbances? For any particular displacement, the circular section of the piece may be considered as though it were resting on another side of the V, shown as a dotted line, a distance *e* from the obstructed side. This displaced side of the V, together with the opposite side, forms a new V, which defines the displaced position of the circular section. The change in the position of the center of the workpiece section, brought about by the bump or particle, is the same as the shift in the apex point from the original V to the new V. Thus, in Fig. 174C, the original V is represented by *BOE*, and the V resulting from displacement is *AO'E*. The axis of the workpiece is displaced an amount equivalent to 00′. For a constant displacement *e*, 00′ is a minimum when $2\alpha = 90°$, or $\alpha = 45°$.

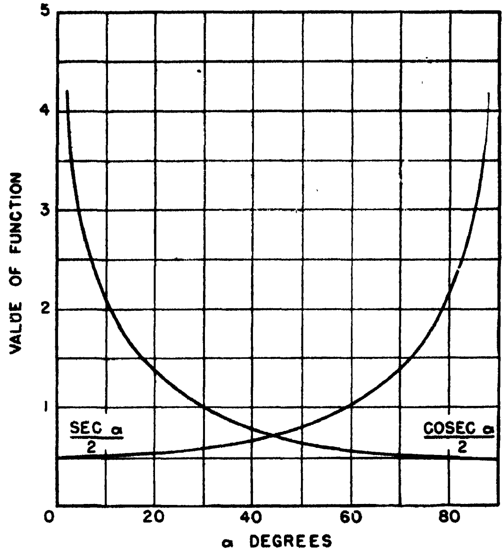

Fig. 173. Curves of two trigonometric functions for V-locators.

Problem 63. Show that the component of displacement

$$O'D = \frac{\sec \alpha}{2} e$$

and
$$OD = \frac{\operatorname{cosec} \alpha}{2} e$$

In other words that the components of displacement of the work center for a constant error e, are proportional to sec $\alpha/2$ and cosec $\alpha/2$, the two curves shown in Fig. 173. Under what conditions might it be desirable for α to be other than 45°, where the two curves intersect?

The Position of a V-locator. Where cuts are to be taken on a cylindrical workpiece concentric with its axis, like drilling the axial hole in the jig of Fig. 168, variations in the diameter of the piece, irregularities, and foreign disturbances will displace the axis proportionally wherever the V is placed. Care should be exercised not to place the locator where it is more likely to make contact with recurring irregularities, such as flash lines. An included angle of 90° in the locating V normally will result in the minimum displacement from any irregularity.

Where cuts are to be taken in planes perpendicular to the axis of a cylindrical workpiece, the placement of a V-locator is important. An instance is cross drilling. A V-locator with its center plane at a right angle to the axis of the bushing causes the largest displacement of the axis from differences in workpiece diameters, as shown in Fig. 175A. If the drill bushing is placed in line with the center C_1 of section 1, a piece 2 of different diameter has its center C_2 in a different position. On the other hand, if the central plane of the V-locator is placed in line with the axis of the bushing, like in Fig. 175B, differences in diameters, like 1 and 2, cause a change in axial position but no shift in relation to the axis of the bushing.

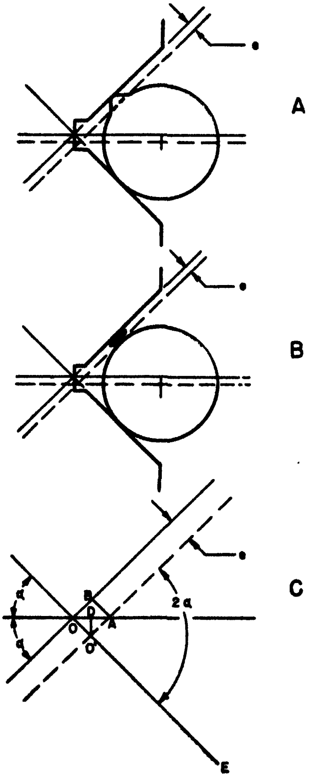

Fig. 174. The effect of irregularities on V-location.

Cylindrical locators

A piece fitting snugly on a plug, like in Fig. 176A, has lost four degrees of freedom. In any two co-ordinate planes containing the axis of the plug, the block can be considered as having four points of contact, near the ends of the locating hole, which account for the confinement. The block still can move parallel to and rotate about the axis of the plug. If the plug has a shoulder, against which the block is held, like in Fig. 176B, a fifth degree of freedom is lost. Rotation about the axis of the plug remains; and to restrain that, the block may be held against a stop, like in Fig. 176C. Thus, positive location may be secured by placing a workpiece with a hole in it, on a cylindrical plug, providing an axial stop, and fixing one point to prevent rotation about the axis of the locator.

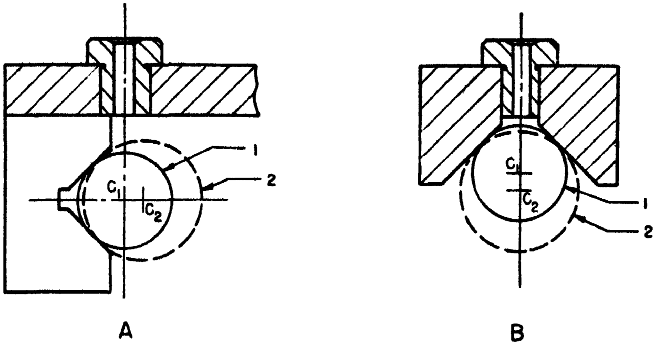

Fig. 175. The placement of a V-locator. For drilling through the axes of cylinders of different diameters, location should be taken in a V with its axis in line with the axis of the drill bushing.

The piece containing the hole may be considered the fixed locator and the plug of Fig. 176 the object to be located. The conditions are the same as those in the reverse situation except that rotational fixation must be referred to the plug, as indicated by the arm held against the track in dashed lines in Fig. 176C.

Except for a press fit, a plug and hole are always subject to some possible misalignment, as indicated in Fig. 177. The amount by which the axes may diverge, expressed in inches per inch, is equivalent to $(D_1 - D_2)/L$. The meaning of the letters is defined in Fig.

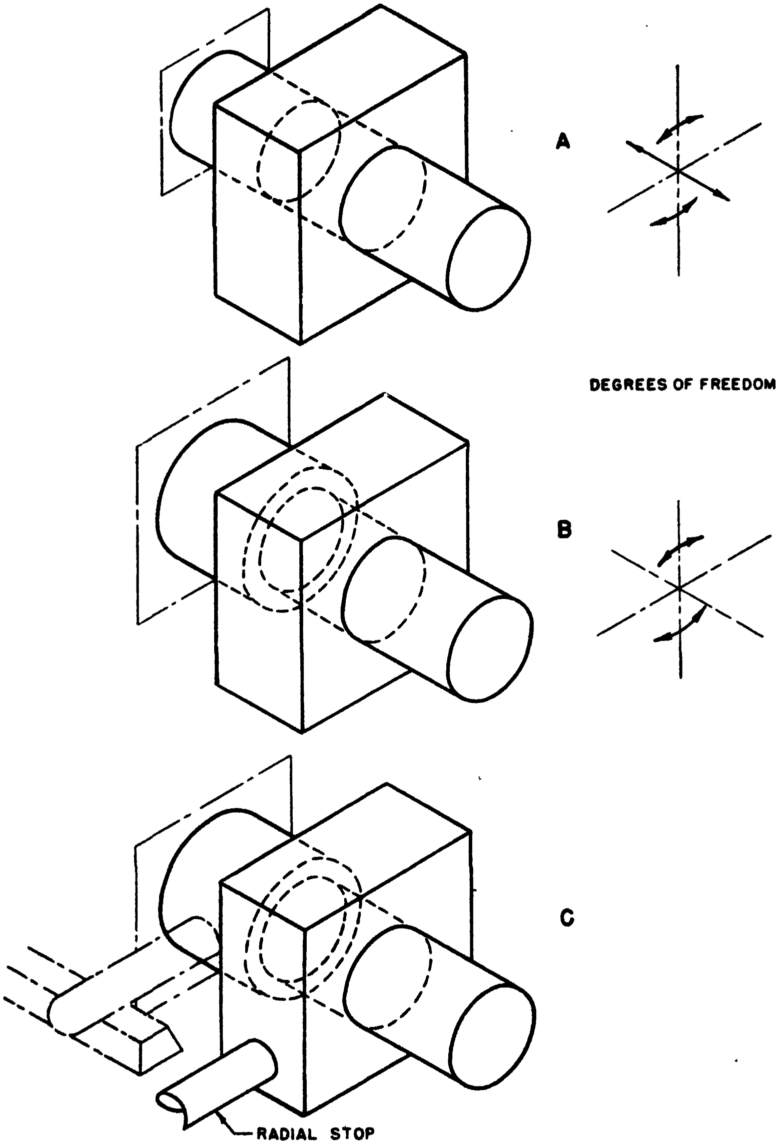

Fig. 176. Elements of cylindrical locating.

177. As the difference between the diameters increases or the length of contact decreases, the misalignment becomes greater. The diversity allows a limited amount of rotation. In some cases, it may not be objectionable, but where the length of contact is short, the resulting rotational freedom may be appreciable, even though the difference between the diameters is small and radial movement is not exorbitant.

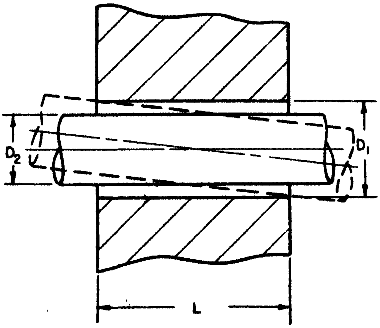

Fig. 177. Misalignment between plug and hole.

To reduce the misalignment resulting from looseness between a locating plug and the hole in a workpiece, a plane-locating surface, square with the axis of the plug, may be used. Three points may represent the plane. An example is shown in Fig. 178. Three degrees of freedom are confined by resting the piece on the horizontal surface. The short plug offers two points each in a vertical plane. A radial locator completes location of the piece. This arrangement may be compared with the 3–2–1 placement of points in plane locating. The base plane contains the three points to eliminate vertical motion and rotation in two directions; one point on the plug and the radial stop furnish two points in a vertical plane to prevent one horizontal movement and the third rotation; and another point on the plug acts as the point in the third of three mutually perpendicular planes to take care of the remaining horizontal motion.

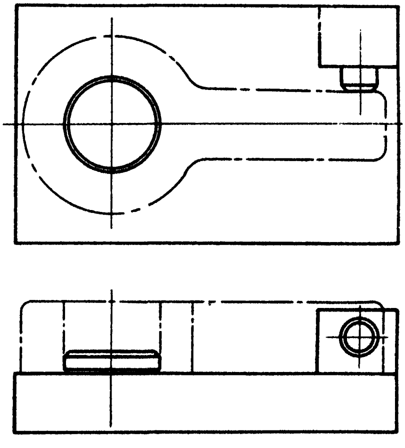

Fig. 178. A workpiece located on a plane, over a short plug, and by a radial stop.

Figure 179 is a sketch of a gage in which the stem of a bevel gear is located in a hole for checking the teeth. Axial position is determined from the thrust shoulder of the gear in contact with the top of the bushing.

Figure 180 presents an example of location taken on two cylindrical surfaces, each at the opposite end of a shaft.

The jig of Fig. 198 locates the large bore of the master rod, for which it is intended, from two plugs in line, one attached to the base and the other to the bushing plate. A base-locating surface is also provided by the heads of the bushings and the shoulder of the pin on the outboard locator. Actually with the base plane, only the one short plug is needed in the main bore. The upper plug serves the additional purpose of correcting any slight misalignment of the bushing plate by pulling it into position.

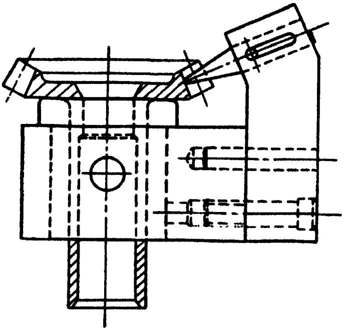

Fig. 179. A gage for checking the teeth of a bevel gear. The gear is located on its stem in the bushing and from the thrust shoulder against the top of the bushing.

Conical locators

A round plug must be below the minimum diameter of the hole in the workpiece it is to locate. If the diameter of the hole is subject to considerable variation, as it usually is in a semi-finished or rough piece, the lateral movement of any piece with respect to the locator is likely to be quite wide. To overcome this variation and centralize the hole, a conical or tapered plug may be used instead of a straight plug. An adaptation of this sort is shown in Fig. 181, where a rough piece resting on buttons is centered from the rough hole by a tapered plug brought down with the bushing plate.

A tapered plug to compensate for large variations in the size of a hole makes contact in practically one plane normal to its axis. Three points in another plane are also necessary to square the workpiece. This is provided in the base of Fig. 181. Since the extent to which the plug enters the hole varies with the hole size, the distance from the member carrying the plug to the workpiece surface is subject to considerable variation. The plug carrier is, therefore, not a suitable locator itself, unless the plug is made to slide in it.

Turning on centers, one of the commonest processes for both

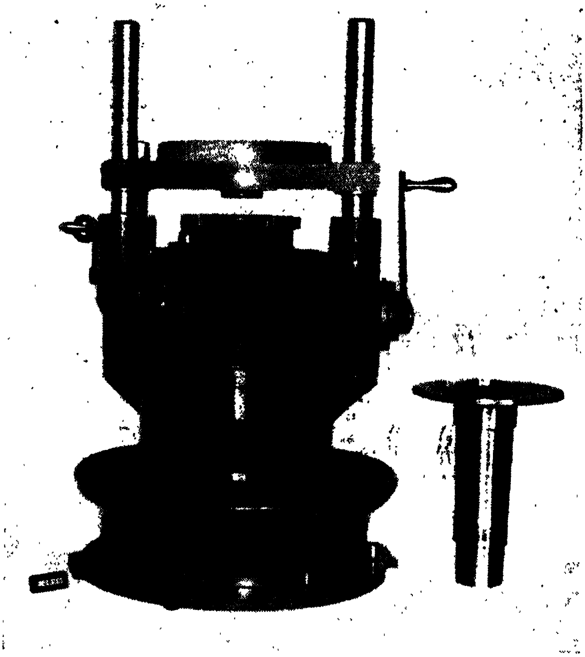

Fig. 180. A flanged shaft located on cylindrical surfaces at its ends. Closely spaced holes are drilled in a circle in the flange. The jig rests on a two-station index base. The holes are drilled in two settings because of their close spacing.

The bushing plate carries a plug which comes down into the hole of the piece. The lower adapter can be changed for various parts of different lengths. (Courtesy Swartz Tool Products Co., Detroit.)

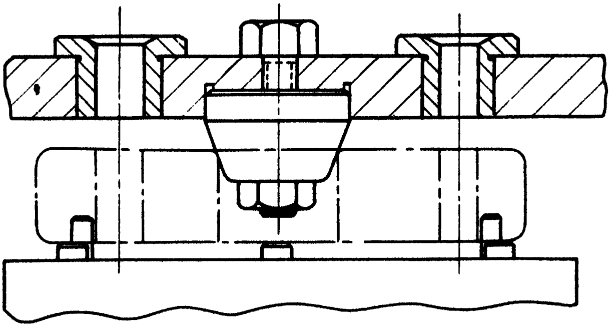

Fig. 181. A rough workpiece centered by a conical locating plug.

rough and finished work, utilizes location from tapers. Normally, the holes in the workpiece are formed to the same taper as the centers to increase the length of contact and reduce the effects of wear. Two centers, one in each side of a workpiece, provide means for eliminating five degrees of freedom. A centered workpiece can be taken from machine to machine with a high degree of accuracy in relocation, particularly with respect to concentricity of different diameters on the same piece. Variations in the diameters of center holes do introduce discrepancies in endwise location. For consistent axial location when the center holes vary in diameter, a spring center like that shown in Fig. 182, may be used. There the end location is independent of the size of the center hole as the end of the piece is pushed against the fixed face around the center.

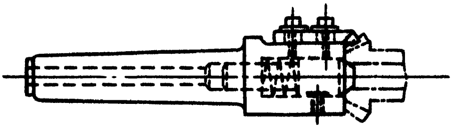

Fig. 182. A spring center for a grinder headstock. End location is taken from the face of the center body. The tapered center plug is pushed into the center hole of the workpiece by the spring to compensate for variations in sizes of center holes.

A round, rough workpiece cannot be located dependably in a cylindrical nest for the same reason that a straight plug is not a close locator for a rough hole. A cylindrical nest for a rough piece must not be smaller in diameter than the largest allowable diameter of the piece. The smallest workpiece is much less and would be a very loose fit. For rough round sections, *a nest in the form of an internal cone* is used. The actual contact may be made on edges along elements of the cone, as shown in Fig. 183. In that jig a transmission-cluster-gear forging is located among conical elements at top and bottom, so that a hole may be drilled concentric with the average contours of the ends. The edges of the lower locators are sharp to dig into the workpiece under the drill thrust and keep the piece from turning with the drill.

The barrel of the shifter fork in Fig. 43 is located at the bottom in a conical nest, so that the drilled hole is centralized with the outer edge.

A common clamping and centering device using the conical principal is the screw bushing with an internal taper in the contact end. One is shown in Fig. 184. The workpiece rests on the lower plate of the jig and is centered from the boss by a screw bushing. The friction resulting from clamping and drill thrust deters rotation of the workpiece. No provision is made for radial location, and none is needed for drilling centrally with the boss.

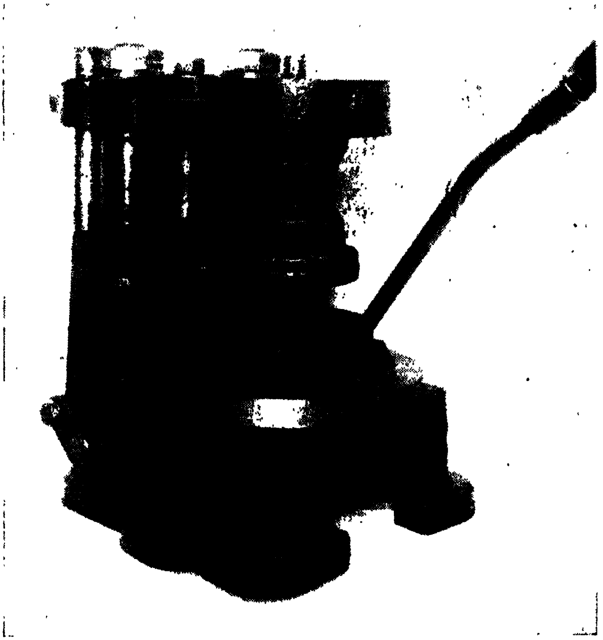

Fig. 183. An example of conical location. A universal jig is equipped with locators at top and bottom which have the effect of contacting the transmission cluster gear forging between conical elements. The forging is centralized at both ends with respect to its outside surface to which the hole is drilled concentrically. The drill thrust presses the piece against the sharp edges of the lower locators, which dig in and counteract the torque of the drill.

Jigs of this sort can be mounted on presses with automatic power feed, and one operator can handle six to eight jigs. (Courtesy Swartz Tool Products Co., Detroit.)

Long finished tapers and sockets are the ideal examples of this class of locators. They locate through close confinement of five degrees of freedom. The tapered shanks on such tools as drills and milling machine arbors, and the tapered machine spindle holes in which they fit, are common examples.

A tapered mandrel with a small gradient may be pressed into a straight finished hole. Sufficient force is applied so that a tapered fit is impressed over an appreciable length of contact. A decided disadvantage from the standpoint of production is that variations in positions taken by different workpieces along the axis are large.

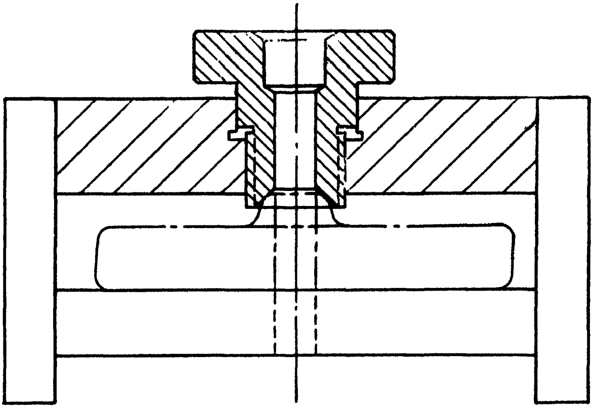

Fig. 184. A rough blank located from its hub by an internal cone in the end of a screw bushing.

Radial location

Radial location does not mean location in a radial direction, but rather the fixation of one radius to establish the positions of all radii emanating from the axis of a piece. V-blocks, plugs, holes, or conical locators must have supplementary means for radial location. Radial locators are of two types:

1. Those that fix the location of a definite external point on a piece.
2. Those that position a geometric point or axis within a body with respect to tangible surfaces.

The first type is exemplified in Fig. 178, where a point on a wing of the part shown is held against a button.

The second type may be divided into two classes, pin locators and centralizers, which will be described in the next few sections.

A basic rule for all radial location is that the fixation point should be taken as far from the axis of radiation as possible, to minimize the errors of location. The reason for this is demonstrated in Fig. 185. A displacement *d* at a distance *a* from the axis *O* results in an angular error of *AOA′*. The same displacement *d* at a greater distance *b* gives an angular error *BOB′*, which is smaller.

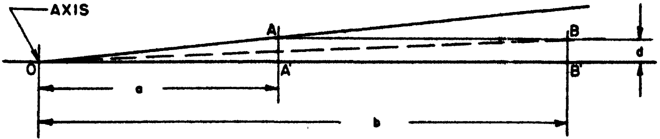

Fig. 185. Points for radial location should be placed as far apart as possible.

Dual pin locators. A common means of location consists of two plugs or pins extending from a base surface. These pins are made to fit two accurate holes in each workpiece square with a finished locating surface. The holes may also have a functional purpose, but often one or both are put into the part for the purpose of locating alone. This method of location is widely accepted for cylinder blocks, for instance. That is the reason for the two holes in the lugs at the extremities of the base of the cylinder block shown in Fig. 42. After that block has been finished, the larger hole is tapped and used for an oil-filler hole, but the smaller has no purpose other than locating. A similar cylinder block located from the base and two closely held holes for boring the cylinder is shown in Fig. 142. The larger cylinder block of Fig. 143 is located in the same manner.

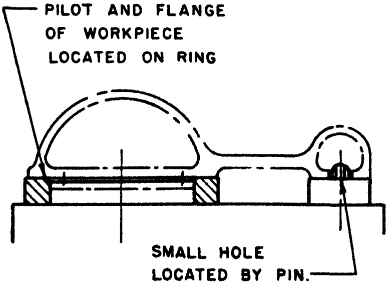
PILOT AND FLANGE OF WORKPIECE LOCATED ON RING
SMALL HOLE LOCATED BY PIN.

Fig. 186. A variation of dual cylinder location. The casting has a large pilot surrounded by a flange, and those two surfaces are located from a ring. A pin in a small hole gives radial location.

The jig of Fig. 198 is constructed to locate a master rod on the large plug, the outboard pin, and the tops of the bushing. Another variation of this method of locating is found in Fig. 186. There a casting has an accurate pilot diameter surrounded by a finished flange face, which fits a ring in the fixture. Radial location is derived from a pin in a small hole at the other end of the piece.

A part located from two pins, like the one of Fig. 187, may be considered as deriving its principle location from the base plane and one pin, such as the pin at *A*, and radial location from the other pin, say *B*. In other words, the base plane takes care of 3 degrees of freedom and one pin *A* eliminates movement in directions *x* and *y* through its axis. The only remaining need for pin *B* is to prevent rotation about the axis of *A*, which is done by elimination of movement in the *y* direction through the axis of *B*. Thus, the second pin needs to fit the hole, *B*, on only two sides.

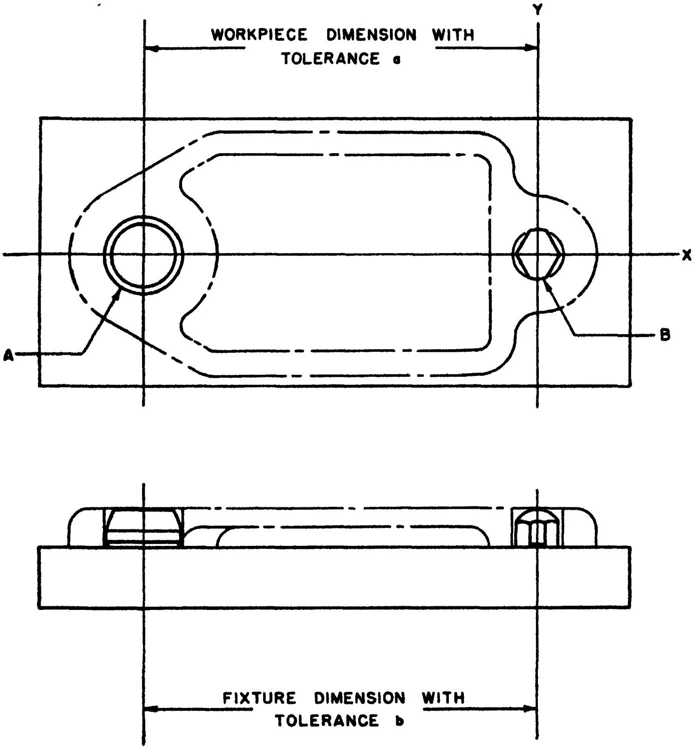
Y
WORKPIECE DIMENSION WITH TOLERANCE a
X
A
B
FIXTURE DIMENSION WITH TOLERANCE b

Fig. 187. A part located from two pins and a base surface.

Between the centers of the holes *A* and *B*; the part has a dimension with a tolerance *a*. Between the centers of the locating pins *A* and *B*, the fixture must likewise have a dimension with tolerance *b*. For accurate location, there should be an allowance between plug *A* and hole *A* of only a few ten-thousandths of an inch. But if pin *B* is a complete cylinder, the allowance between pin *B* and hole *B* must be at least as great as the tolerances *a* and *b* of the dimensions between hole and pin centers. This is so that the holes will pass over the pins in all permissible positions. As a result, there will be considerable play between the hole and pin at *B* in the *y* direction, which is contrary to the purpose for which pin *B* is intended.

Diamond pin locators. For a radial locator, a widely used item is the diamond pin, a typical plan view of which is shown in Fig. 188. It is relieved on two sides to allow for deviations in hole position in the *x* direction and has two cylindrical segments, of width *W*, to match the hole in the *y* direction. The least radial movement of the piece occurs when the diameter, *d*, of the pin is smaller than the diameter, *D*, of the hole by only what is needed to slip the smallest size hole over the pin.

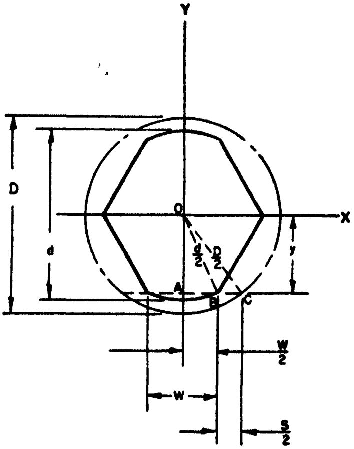

Fig. 188. Enlarged view of diamond locator pin, at *B* in Fig. 187.

To allow for variations in the position of the hole, the contact width *w* must be short enough to leave a clearance $S/2$, such that S is equal to or greater than the sum of the tolerances, *a* and *b*, of the center distances between the holes and between the pins. From the two triangles, *OAB* and *OAC*, the following relationships are evident:

$$Y^2 = \frac{d^2}{4} - \frac{W^2}{4} = \frac{D^2}{4} - \frac{W^2}{4} - \frac{2WS}{4} - \frac{S^2}{4}$$

and

$$2WS = D^2 - d^2 - S^2$$

$$W = \frac{(D + d)(D - d)}{2S} - \frac{S}{2}$$

$$= \frac{[2D - (D - d)](D - d)}{2S} - \frac{S}{2}$$

$$= \frac{2D(D - d)}{2S} - \frac{(D - d)^2}{2S} - \frac{S}{2}$$

but $(D - d)$ is small, of the order of 0.001 in. Therefore, $(D - d)^2$ is much smaller, of the order of 0.000001 in., and the term $\frac{(D - d)^2}{2S}$ is negligible in comparison with the other terms. Thus:

$$W = \frac{D}{S}(D - d) - \frac{S}{2} \tag{77}$$

This means that:

1. The larger the nominal size of the hole, the larger the permissible width of contact surface of the pin for the same allowance between pin and hole and the same tolerances on the hole center and pin center distances.
2. As the tolerances between the hole centers and pin centers increase, the permissible width of contact surface on the diamond pin grows less, if the diameters and tolerances of the hole and pin are unchanged.
3. If, for a practical tolerance between hole centers and a prescribed size of radial locating hole, the permissible width of contact (W) of the diamond pin is insufficient for endurance of the pin; then the allowance $(D - d)$ between the hole and pin must be increased. The allowance should be as small as it can be and still leave enough surface width (W) to resist wear and allow the plug to enter all holes. For hardened steel pins, acceptable practice[1] permits a width W as small as $\frac{1}{8}$ of the nominal diameter of the hole in which it locates, but not less than about $\frac{1}{32}$ in.

EXAMPLE 24: The part of Fig. 187 has two locating holes with center distance of 8.00 ± 0.002 in. The center distance between pins is 8.000 ± 0.0002 in. Hole A is nominally 1 in. in diameter, and hole B $\frac{1}{2}$ in. diameter. The allowance for pin B is 0.0006 in. What is the maximum permissible width of diamond pin contact in hole B? Does it meet accepted practice?

For the width of pin contact:

$$W = \frac{0.5}{0.0044}(0.0006) - \frac{0.0044}{2}$$
$$= 0.0682 - 0.0022 = 0.066 \text{ in.}$$

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[1] B. R. Garrett, "The Use of the Diamond Pin in Locating Work," *The Tool Engineer*, December 1945, Vol. XV, No. 5, page 32.

Suitable minimum width of contact for a $\frac{1}{2}$-in. diameter pin is $\frac{1}{2} \times \frac{1}{8} = \frac{1}{16} = 0.0625$ in. Therefore, the diamond pin meeting the conditions of the problem is adequate.

Problem 64. If the center distance dimension between holes A and B of Example 24 has a tolerance of ± 0.005 in., what width of contact (W) must be provided for pin B of 0.4994-in. diameter? The minimum hole size is 0.5000 in. To what diameter must the pin be reduced to give a width of contact (W) equal to or greater than $\frac{1}{16}$ in.?

Problem 65. Derive the exact expression for d in terms of D, W, and S.

Problem 66. Show that when $W = D/4$; $S = 4e$, where $e = (D - d)$. Neglect terms of e^2.

Problem 67. The 10° ± 15′ angle of the part shown in Fig. 189 is to be checked by placing the piece on the gage sketched for it. The 0.750 ± 0.001-in. diameter hole is to be placed over the straight pin, and the 0.375 ± 0.0005-in. diameter hole over a diamond pin. Specify the diameter and contact width (W) of a suitable diamond pin.

Problem 68. For a 0.045-in. wide contact face, calculate the pin diameter for the gage of Fig. 189 by the exact expression derived in Problem 65. Also calculate the diameter by Eq. (77). What is the discrepancy of the approximate equation?

MEAN LOCATORS

Centralizers

In Fig. 178 the radial locator is a button against which one side of a wing of the part bears. If this is a rough part the center of the section may vary considerably in its location from piece to piece. Even if the sides are finished, some variation can be expected. If it is necessary to cut a groove or drill one or more holes in line with the center of the wing, the manner of location is obviously inadequate. What is needed is a means of setting the center of the section in a definite position each time a piece is located. This is known as *centralization.*

A *centralizer* is a device that forces two, and sometimes more, opposed points into positions where they are equidistant from a fixed point. Thus, in effect, the centralizer locates the center point between the spots it contacts. At the same time a centralizer performs a certain clamping function.

There are many types and variations of centralizers. For detailed descriptions of the different kinds, the student is referred to standard books of tool design. To illustrate the principle of centralization, a few examples only are given here.

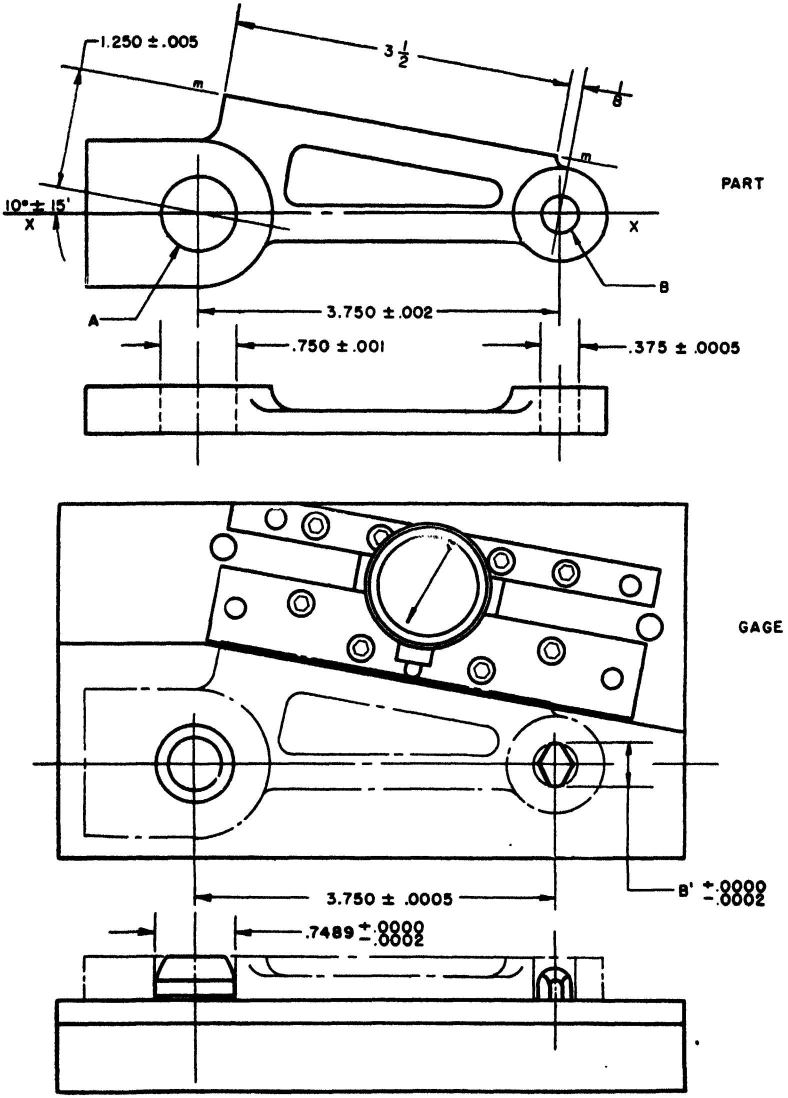


Fig. 189. A workpiece and a gage to check the angle and position of an edge.

The movable V-block of the jig of Fig. 170 is one of the simplest of centralizers. It brings the center of one round end of the piece into position along an axis which bisects the angle of the V. This emphasizes an important characteristic of every centralizer; that for each two points contacted, one point is really located.

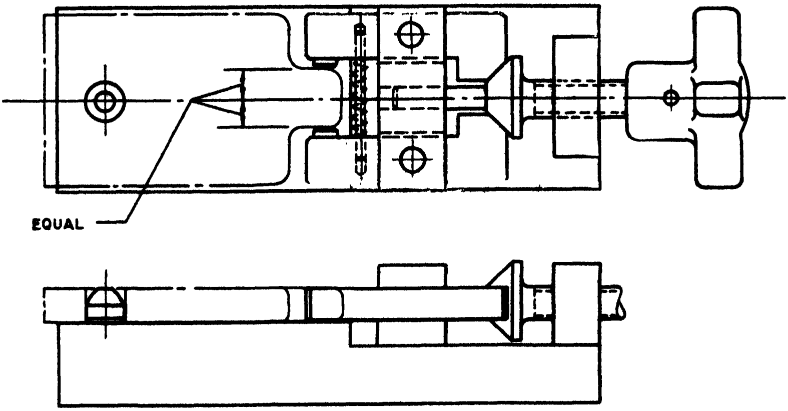


Fig. 190. An external centralizer in the role of a radial locator.

In Fig. 190 a workpiece resting on a plate would be free to rotate about a pin except for the centralizing arms which locate the center of the lug between the two points of contact. The piloted cone on the screw is advanced to spread the pivoted arms apart at one end, causing the contact buttons on the other side of the pivot to move equidistantly with respect to a fixed axis. When the cone is withdrawn, a spring parts the clamping end of the centralizer.

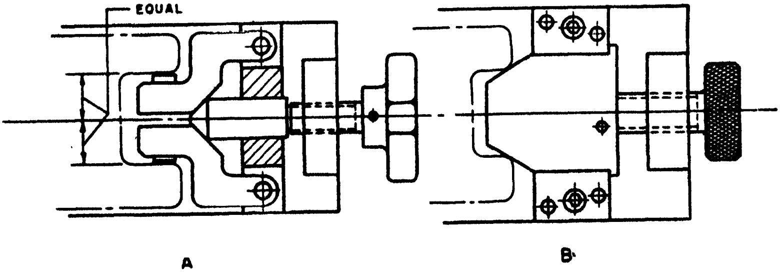


Fig. 191. (A) One type of internal centralizer. (B) A wedge used as an internal centralizer.

In Fig. 191A the cone point of the screw spreads the centralizing arms apart to contact internal surfaces on the workpiece and locate these surfaces at equal distances from the predetermined axis. Another internal centralizer utilizes a wedge as sketched in Fig. 191B. This locator contacts the piece on two edges, whereas the centralizer of Fig. 191A can be made to reach what may be more desirable spots away from the edges. The wedge-type centralizer is simple and has found acceptance where edge contact is not undesirable.

Although centralizers have been shown in the role of radial locators, their use is not confined to that function. Each primary centralizer establishes a point to eliminate a degree of freedom and thus may be used in conjunction with any other locating means. For instance, a centralizer may be used near each end of a long piece to locate its centerline so that a series of holes can be drilled centrally with its sides. With that arrangement, an end stop and base plane are necessary to complete location.

Gear tooth locators

Next to the basic surfaces of planes, cylinders, spheres, and cones, the involute is probably the most frequently encountered surface because of its wide use for gears. Consequently, consideration of gear tooth location is in order to demonstrate the application of the principles of locating to special forms.

There are *two types of gear locating problems:*

1. The use of a gear tooth or space as a radial locator.
2. Location from several gear teeth, sometimes together with a face, to establish alignment with other surfaces.

In any case, arrangements are usually made to contact gear teeth on the involute profile at the pitch line. The teeth may be modified or have errors at their extremities. The pitch line is normally well inside the extremities and is the standard reference position on a tooth. Also, the dimensions of a gear tooth are usually referred to the pitch diameter and calculations from that reference are simple and more dependable.

Radial location from gear teeth

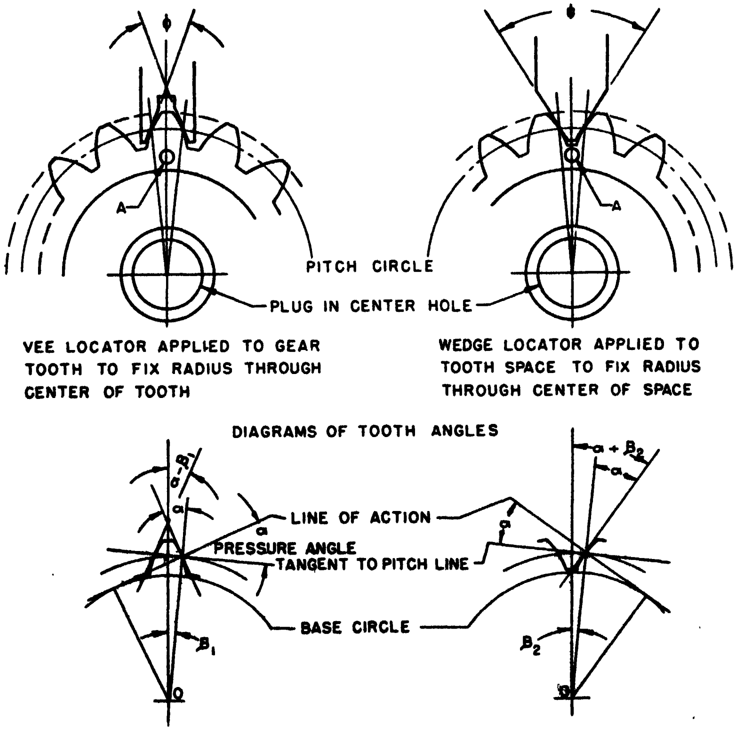
A spur gear tooth may be located radially by a guided V-block brought to bear on both sides. Likewise, a tooth space may be located radially by a wedge or cone bearing in the same way. In Fig. 192 are sketched the outlines of two gears located by plugs in their center holes and positioned to establish the radii on which holes, marked *A*, are to be drilled. The principal problem is to determine the angle of the locator which will insure contact at the pitch line.

For the V, the angle $\phi = 2(\alpha - \beta_1)$, as shown in the diagram of the tooth angles. For the wedge or cone, the angle $\psi = 2(\alpha + \beta_2)$. α is the pressure angle of the gear.

$$\beta_1 = \sin^{-1}\frac{T}{D}$$

where

T = tooth thickness = $\pi/2P - L$ (approximately),



VEE LOCATOR APPLIED TO GEAR TOOTH TO FIX RADIUS THROUGH CENTER OF TOOTH

WEDGE LOCATOR APPLIED TO TOOTH SPACE TO FIX RADIUS THROUGH CENTER OF SPACE

Fig. 192. Radial location from gear teeth.

P = diametral pitch of the gear,
L = back lash of the gear,
D = pitch diameter of gear,

and
$$\beta_2 = \sin^{-1}\frac{S}{D} \tag{78}$$

where S = tooth space width = $\pi/2P + L$.
It may be more convenient to express:

$$\beta_1 = \frac{90}{N} - \Delta \qquad \text{and} \qquad \beta_2 = \frac{90}{N} + \Delta$$

where N = number of teeth in gear, and

$$\Delta \div \tfrac{1}{2}\frac{L}{R_p}\frac{180}{\pi}$$

where R_p = pitch radius.
L is normally small, and for practical purposes,

$$\beta_1 = \beta_2 = \frac{90}{N} \tag{79}$$

Problem 69. What should be the angle of a V-locator for a tooth of a 10 diametral pitch, 20° pressure angle spur gear with 60 teeth and no back lash?

Problem 70. What should be the angle of a cone locator for a tooth space of the gear described in Problem 69?

Problem 71. Show how to calculate the angle of a cone locator for the tooth space of a helical or spiral gear.

Problem 72. A helical gear has a spiral angle of 16° 16′, a pitch diameter of 12.5 in., 48 teeth, and a pressure angle of 20° in its plane of rotation.

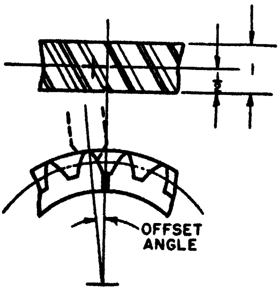


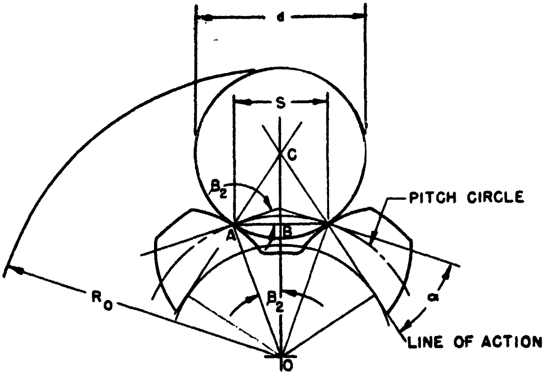
Fig. 193. A sketch of a cone locator for a helical gear.

The gear is 1 in. wide. What should be the angle of a cone locator for a tooth space? Assume no back lash.

The gear is to be set on one side for cutting a groove on the top side, concentric with a radius through a tooth space. The centerline of the cone is midway between the two faces. Through what angle should the radius through the cone axis be offset from the radial axis of the groove? See Fig. 193.

Location from several gear teeth

Rolls or pins, inserted between three pairs of teeth of a gear and gripped in chuck jaws, are commonly used for spur gear location. Two considerations are necessary for specifying this form of tooling. They are: The proper diameter to contact the teeth at the pitch diameter, and the diameter at which the chuck jaws contact the pins.



PIN OF DIAMETER (d) CONTACTS TEETH AT PITCH LINE

Fig. 194. Diagram of angles concerned with size of locating pin.

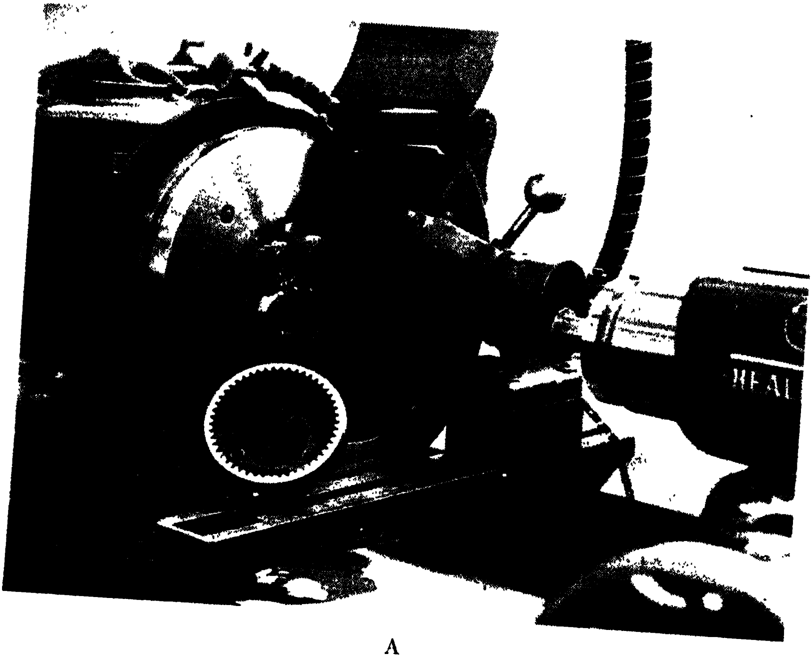
The formula for the size of the pin that just touches two adjacent teeth at the pitch line can be derived from the diagram of Fig. 194. The angle CAB is equal to the pressure angle α plus half the tooth space angle, which is β_2 defined by Eqs. (78) and (79).

$$AC = \frac{AB}{\cos(\alpha + \beta_2)},$$

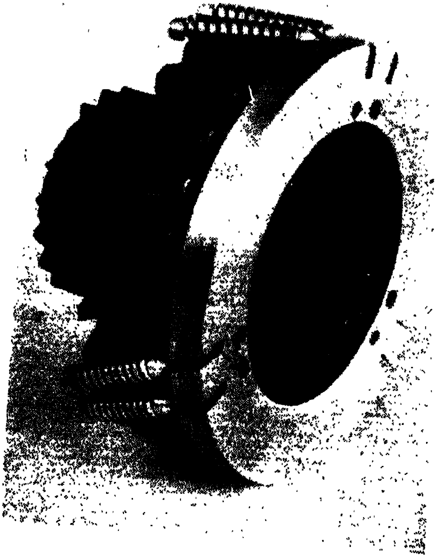
but $$2AC = d \quad \text{and} \quad 2AB = S,$$

so $$d = \frac{S}{\cos(\alpha + \beta_2)} \tag{80}$$

where d and s are defined in Fig. 194.



A



B

Fig. 195. Methods of locating helical gears from the teeth at the pitch line. (A) Pinion-type gear chuck for an internal helical gear. (B) A helical-gear spring roll cage. The rolls in the tooth spaces are contacted by chuck jaws. (Figs. 195, 196, courtesy Heald Machine Co., Worcester, Mass.)

The diameter at which the chuck jaws engage a pin is twice the radius (R_0) of Fig. 194. R_0 is equal to $OB + BC + r$ (the radius of the pin).

$$OB = \frac{AB}{\tan \beta_2} = \frac{S}{2 \tan \beta_2}$$

$$= R_p \cos \beta_2$$

where R_p = pitch radius,

$$BC = AC \sin (\alpha + \beta_2) = r \sin (\alpha + \beta_2)$$

$$= \frac{S}{2} \tan (\alpha + \beta_2)$$

Therefore

$$R_0 = \frac{S}{2}\left[\frac{1}{\tan \beta_2} + \tan (\alpha + \beta_2)\right] + r \tag{81}$$

$$= R_p \cos \beta_2 + r[1 + \sin (\alpha + \beta_2)] \tag{82}$$

Problem 73. Specify the proper diameter of pins and diameter of contact of chuck jaws for holding the gear described in Problem 69.

Problem 74. Specify pin and chucking diameters for a 6 pitch, 24 teeth, 14½° P.A. spur gear with 0.004 back lash.

There are a number of commercial chucks utilizing various means of securing contact on the involute surfaces of gear teeth at the pitch line. A chuck having eccentric pinions is shown in Fig. 195A, for either external or internal spur or helical gears. Each chuck of these types must be constructed for a specific gear. For helical gears flexible rolls held by a cage like those of Fig. 195B may be employed.

Bevel gears may be located in similar ways. Several typical arrangements are shown in Fig. 196.

SUMMARY

Location is essential to place each workpiece coming to an operation in a definite position so that the effect produced on all will be uniform. The first requirement to this end is that an object be confined completely. That can be done by eliminating motion along and rotation about three co-ordinate axes. For this the equivalent of six fixed supports are needed; three in one plane, two in a second plane, and one in a third plane. The most satisfactory arrangement is for these three planes to be at right angles to each other. For some

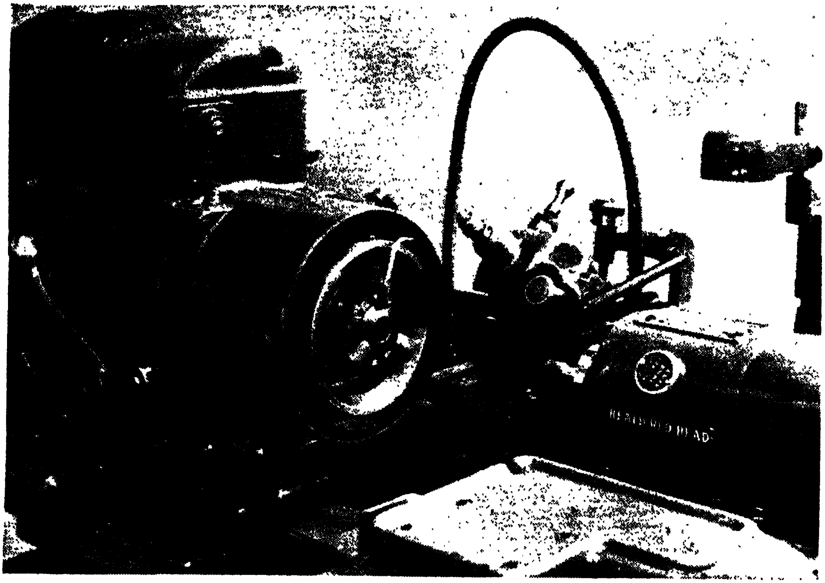


Fig. 196A. A bevel gear located from the pitch line by an adapter plate having slots the same pitch as the gear.

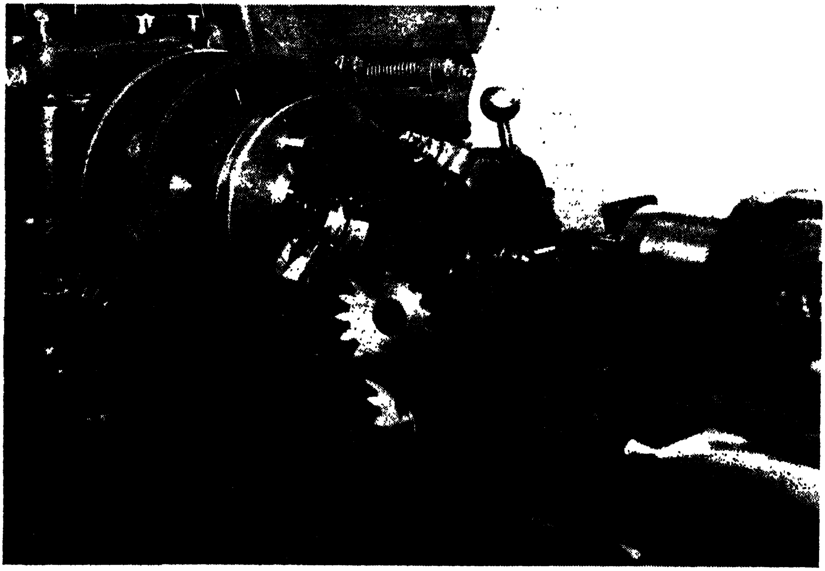


Fig. 196B. A bevel-pinion located on five balls at the pitch line.

applications retention, but not definite location, only is mandatory for one freedom.

Often a number of points are available for satisfaction of the minimum requirements of location. The problem is to select those which are most advantageous. They are indicated by the condition of the workpiece surfaces, the shape of the workpiece, and the nature of the surfaces to which registration is required.

There are rough, semi-finished, and finished surfaces. Rough, and often semi-finished, surfaces require a minimum of locating area. Where reinforcement is needed, adjustable supports must be used. Finished surfaces are subject to less restriction.

To accommodate the common surface forms, plane, cylinder, and cone, several fundamental locating devices are available. Each one, as well as its modifications, is based on characteristic principles that must be recognized to make it fully effective. In addition, unusual surfaces require special arrangements to suit their particular forms. One of the most important considerations for any type of locator is that it gives proper attention to the surfaces that require registration.

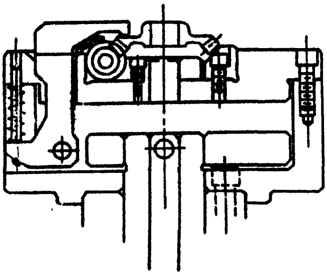


Fig. 196C. A cross section of a chuck for locating from the pitch line of bevel-gear teeth on three tempered rollers for grinding the hole and hub face of the gear. Fingers for holding the gear on the rolls are actuated by an air cylinder.

QUESTIONS

1. What is the purpose of workpiece location?

2. What are the first requirements for workpiece location?

3. What must be taken into consideration in choosing locating points?

4. How may a free body move and rotate? What is necessary for perfect freedom? For complete confinement?

5. When is location established? Give an example.

6. What is the minimum number of points required to withhold all freedom?

7. Explain the principle that defines the most suitable points for locating an object.

8. State the 3–2–1 principle of location.

9. How many points may be used for locating a finished surface in a base plane? Why? How many for a rough surface?

10. What is the principle of least points?

11. What is the principle of extreme positions?

12. How many degrees of freedom does a long V-locator eliminate? A short V? What else is necessary?

13. Why is a 90° included angle usually desirable for a V-locator?

14. What irregularities should be avoided in positioning a V-locator? How should a V-locator be positioned for cross drilling? Why?

15. How many degrees of freedom are taken care of by a long cylindrical locator? A short one? What else is needed?

16. Why are conical locators used instead of cylindrical locators? Name several common conical locators.

17. What is meant by radial location? When is it necessary?

18. What are the two types of radial locators?

19. What is a basic rule for radial location?

20. What shortcoming is likely to be found with dual-pin locators if both pins are fully round? How may it be alleviated?

21. How wide should the width of contact of a diamond pin be?

22. What effect does the size of the hole, in which a diamond pin locates, have upon the permissible width of contact surface on the pin?

23. What effect do the tolerances between hole centers and pin centers have upon the permissible width of contact surface on the pin?

24. When must the allowance between a diamond pin and the hole in which it locates be increased?

25. What is a centralizer? Describe several.

26. How many points must a centralizer touch to locate one point?

27. What are two types of gear locating problems?

28. From what part of a gear tooth surface is location usually taken? Why?

29. What should be the angle of a V to make contact with a gear tooth at the pitch line? A cone to make contact on both sides of the space at the pitch line?

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14 TOOL DESIGN

THE FUNCTION OF TOOL DESIGN

What tool design is

Tool planning determines the process to be used, the operations required, the locating points for each operation, the dimensions and tolerances to be held, and the machines and tools needed to make a part. As described in Chap. 1 and Fig. 3, the tool engineer, in the role of process engineer, writes orders specifying the tools to be designed and made, where they fit into the production plan, and what requirements they must meet. Some orders may go to the purchasing department to buy standard machines and tools; others are issued to the tool designers or outside specialists. The responsibility of tool design is to devise and proportion tools which will most economically meet the requirements called for by the production plans.

A *tool* has been defined as *any device that is capable of working a material into a desired shape, holding it while it is being worked, or measuring it after the work has been completed.* Thus implements used in all industries are described by that definition. In metal working, however, certain items are best known as tools. They are machine tools and accessories, cutting tools, fixtures, jigs, dies, and gages. Also recognized as tools are such adjuncts as collets, sleeves, toolholders, and other devices to hold, drive, and otherwise assist the function of a tool.

Tool design procedure

The responsibility of the tool engineer may be to supervise the designing of tools and approve the designs. Some tool engineers specialize as designers.

There are several ways in which a tool design department may be organized. One tool designer may be assigned to designing all the tools for a certain part. That is known as the "project method" and is commonly found in small plants. Another method is known as the "group method," where each designer specializes in a particular class of tools, like jigs, fixtures, dies, or cutting tools. In large plants a system combining the advantages of both of the first two is often found. Under it, each project is carried on by a senior designer or group leader, who has assistants who specialize on various kinds of tools.

The design of any tool involves three steps. They are:

1. To determine what the tool must do and under what limitations it must perform.
2. To select or invent a device to meet the requirements.
3. To arrange and proportion the device to perform the required task most efficiently.

If tool planning is thorough, the forms describing the process plan tell the tool designer what he must know for the first step. Also, in most cases the general types of tools needed for any operation are indicated by the process plans. For instance, for a drilling operation a jig is usually needed. But for each type of tool, there are many variations. For example, a milling fixture may be required for an operation, but for any fixture there are many possible clamping arrangements. The second step of tool design is to find an arrangement suitable to the case at hand.

Success in carrying out the second step of tool design depends upon an acquaintance with the various types of tools and a large number of their modified forms. Brief descriptions of some of the common types of tools will be given in this chapter to introduce the subject. For a more complete picture of tools and their details, the student is referred to books devoted to tool design.

After the general form of a tool has been determined, it still must be arranged and proportioned to do a specific job efficiently. That is the third step and involves the three main considerations of (a) economy, (b) the nature of the operation, and (c) accuracy.

How these considerations enter into the design of tools will be discussed.

TYPES OF TOOLS

Machine tools

A distinguishing feature of machine tools is that they *are capable of reproducing themselves or other machines.* The true machine tools are the lathe, milling machine, drill press, planer, and shaper. Others, such as the turret lathe, boring mill, and multispindle drill press, are modifications of the basic types and are usually accepted in the same class. Other tools serve to augment and supplement the activities of these basic machines of industry. In designing almost all tools, the designer must take machine tools into consideration. Not infrequently he is called upon for attachments to become integral parts of machine tools, like a high-speed extra head. He may have to design special machine tools or rearrange standard ones, like that of Fig. 66.

Fixtures

A fixture is defined as *a device for holding work while an operation is being performed.* It also usually locates the work.

Fixtures may be classified according to the kinds of operations in which they are used. Some of the common types of fixtures are the following:

1. Milling fixtures, like those shown in Figs. 32, 46, 65, 70, and 71.
2. Lathe and turret lathe fixtures.
3. Boring fixtures, like Figs. 141 and 142.
4. Tapping fixtures, like Figs. 31 and 47.
5. Drilling and tapping fixtures, like Figs. 41 and 48.

For any one kind of operation, there is usually a variety of fixtures of different constructions. A fixture is often given a name descriptive of one or more features, like:

1. The vise fixture of Fig. 61. It is economical practice to hold small and medium size parts of irregular shapes in special jaws attached to standard vises.

2. Chucks with special jaws. A fixture of that kind is shown in Fig. 58. A collet chuck fixture, in which many sizes of collets may be used, is shown in Fig. 20.

3. A plain fixture which locates a piece in a normal position

to a horizontal plane, as illustrated in Figs. 65, 70, 71, and 142.

4. A face plate fixture.
5. A V-block fixture, like those of Figs. 169, 222, and 225.
6. An air-operated fixture, shown in Fig. 53.
7. A gear tooth fixture, like those of Figs. 195 and 196.
8. The indexing fixtures of Figs. 142, and 143. Fixtures may be mounted on a standard base, like in Fig. 231. A sketch of one form of indexing mechanism is shown in Fig. 197.
9. Universal fixtures which are adaptations of commercial devices like that of Fig. 225.

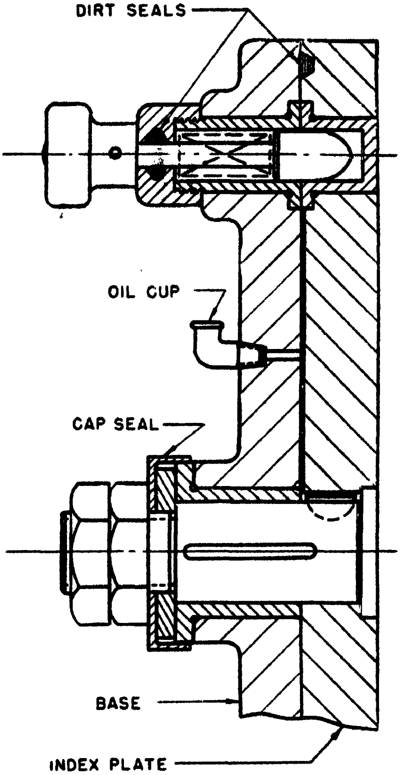

Fig. 197. A section of one form of index plate and base. The device is fully enclosed and protected.

Jigs

A jig is defined as *a device for holding and locating a workpiece and guiding a tool that performs an operation.* Some jigs are fastened in alignment with the cutting tool, but for the most part they are movable.

Jigs are used in only a few kinds of operations. They may be designated by the operation (like drilling, reaming, or boring), but more often are classified according to features of construction. The common types of jigs are the:

1. Plate jig, like that of Fig. 42. A circular jig of the same type, with a round locating ring to fit the workpiece, may be known as a ring-type jig. Jigs of this class are essentially templates, and the simpler ones often carry the name of template jig.
2. Channel jig, as detailed in Figs. 91 and 92.

3. Box jig, like in Figs. 40 and 168. It is not always necessary that such jigs be fully enclosed.

4. Leaf jig, like Fig. 170. Channel or box jigs may have leaves, like in Figs. 40 and 170, and thus fall into two classes.

5. Diameter jig, as detailed in Fig. 93.

6. Open-type jig, shown in Fig. 218.

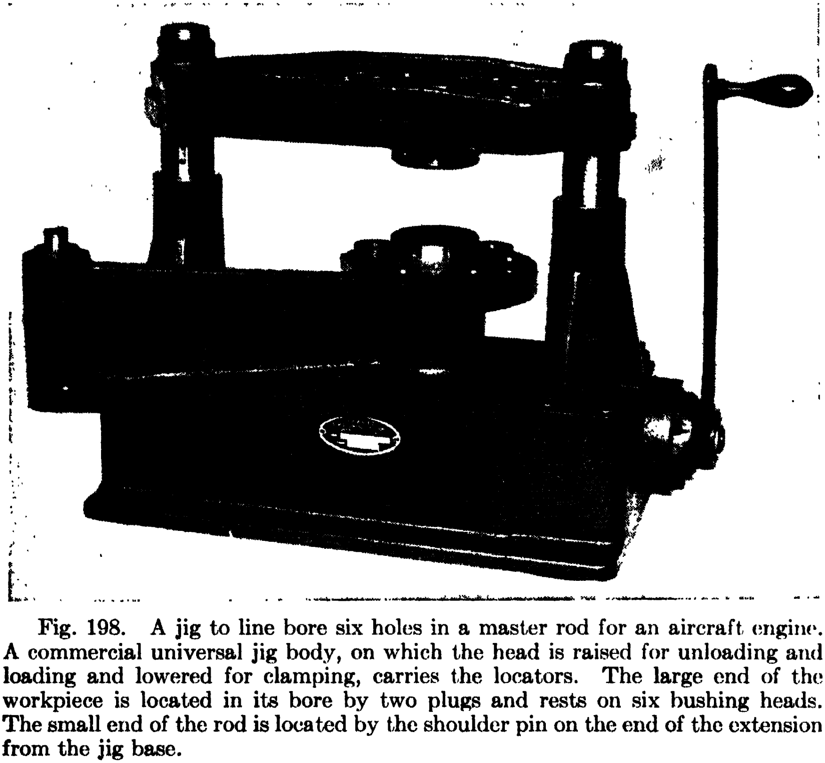

Fig. 198. A jig to line bore six holes in a master rod for an aircraft engine. A commercial universal jig body, on which the head is raised for unloading and loading and lowered for clamping, carries the locators. The large end of the workpiece is located in its bore by two plugs and rests on six bushing heads. The small end of the rod is located by the shoulder pin on the end of the extension from the jig base.

The locating plugs, pin, and bushings are hardened inserts to resist wear. A minimum area contacts the workpiece, to reduce cleaning effort and the possible effect of chips on the locators. (Courtesy Swartz Tool Products Co., Detroit.)

7. Universal jig, built from a commercial body, like in Figs. 43, 44, 171, 183, and 198.

8. Vertical stand jig on which the workpiece is held on an upright wall. Small jigs of that sort are sketched in Fig. 33.

9. Index jig, like Fig. 180.

Obviously many jigs fall into two or more of the foregoing classes.

Cutting tools

Cutting tools are devices that remove metal in the form of chips from parent metal. Power is applied to them for producing definite workpiece shapes.

Cutting tools may be divided into two classes. One class includes single-point tools, such as those used in turning, facing, boring, shaping, and planing; the other includes multitooth cutters such as drills, reamers, counterbores, milling cutters, broaches, and saws. A cutting tool is usually named for the type of operation in which it is used, such as "lathe tool," "milling cutter," or "drill." The material, like high-speed steel, or cemented carbide, may be part of the designation of a tool.

Many standards have been set up[1] for the design and construction of cutting tools. These specify standard features, sizes, and tolerances. Commercial tools can be bought more cheaply than they can be made in small quantities. Where entirely special cutting tools must be designed and made, data available in reference and handbooks can be depended upon for assigning proper angles, dimensions, and tolerances.

Dies

Dies are used in many processes, but the commonest are those which cut or shape sheet metal. They are given the name of press dies to distinguish them from others used in hammers, molding machines, and so on.

Dies that cut sheet metal include stamping dies for blanking and piercing, like those shown in Figs. 56, 62, and 63, trimming, cut-off dies, and shaving dies. In blanking, the piece punched from the strip is the part wanted. In piercing, scrap is punched out of holes in the part. Trimming removes excess metal from the edges of a part. Shaving dies are similar to blanking dies but remove very little stock and cut to close tolerances and straight edges.

Dies for shaping sheet metal include those for drawing, forming, and bending. Drawing is a severe operation producing relatively deep cavities and causing the metal to flow and stretch. Cups, like those in Figs. 24 and 26, are produced by drawing. Forming and bending are shallow processes in which there is less tendency for the metal to wrinkle.

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[1] See, for example, the A.S.A. bulletins of cutting tool standards listed in the bibliography at the end of this chapter.

Among other common types of dies are those used for embossing, coining, broaching, sizing, burnishing, and assembling. The first two types work the metal by upsetting, flowing, and forcing the mass into special forms. In embossing, the piece is bent into a pattern, raised on one side, and depressed on the other. In coining, the metal is forced into dies bearing on both sides to make clear cut designs in relief on the surface of the object. "Hard" money is coined. Fig. 22 furnishes an example of a broaching die. In sizing and burnishing dies, the cut surface of a piece is rubbed smooth. Assembling dies are used for riveting, staking, or otherwise fastening pieces together.

Several operations often are performed within one die. Such dies may be progressive, compound, or indexing. If the operations (piercing, blanking, drawing, and bending for instance) are done in sequence during each press stroke, the die is a progressive die. During one stroke of the press, a series of pieces are acted upon, each in a different station. A sketch of a simple progressive die for piercing and blanking is in Fig. 89. Where two or more operations are performed simultaneously on the same piece during a single stroke, the die is a compound die. A cross section of a compound die for forming and blanking a piece is shown in Fig. 199.

Gages

A gage is defined[2] as *a device for determining whether or not one or more of the dimensions of a manufactured part are within specified limits.* Gages are intended for checking parts quickly in production, to avoid making actual measurements.

A gage usually receives its name from a distinguishing feature of its form or shape. Common types are ring, receiving, plug, snap, thread, form, and flush pin gages. A ring gage has an accurate inside circular surface, like the one in the upper left-hand corner of Fig. 200. A receiving gage has a noncircular hole to receive a part of the proper size. One is shown in the center of Fig. 200. A plug gage has an outside gaging surface to fit a hole. It may be round, tapered, or irregular in shape. Several common types are shown in Fig. 200. Snap gages appear at the top center and in the bottom left-hand corner of the same figure. Thread gages also are shown. A form gage, as the name implies, checks a form or contour. Gages of that type, made from flat stock, are shown next to the snap gages of Fig. 200. A flush pin gage is in Fig. 50.

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[2] *Tolerances, Allowances, and Gages for Metal Fits,* A.S.A. B4a–1925, page 4, American Standards Association.

According to other features, a gage may be fixed (solid), adjustable, indicating, or optical. Some snap gages are fixed for the limits of a dimension, others are adjustable within a certain range, and others incorporate indicators to show size. One kind of indicator gage is in Fig. 201. An optical comparator or projector magnifies images of objects and throws them on a screen for comparison with a master.

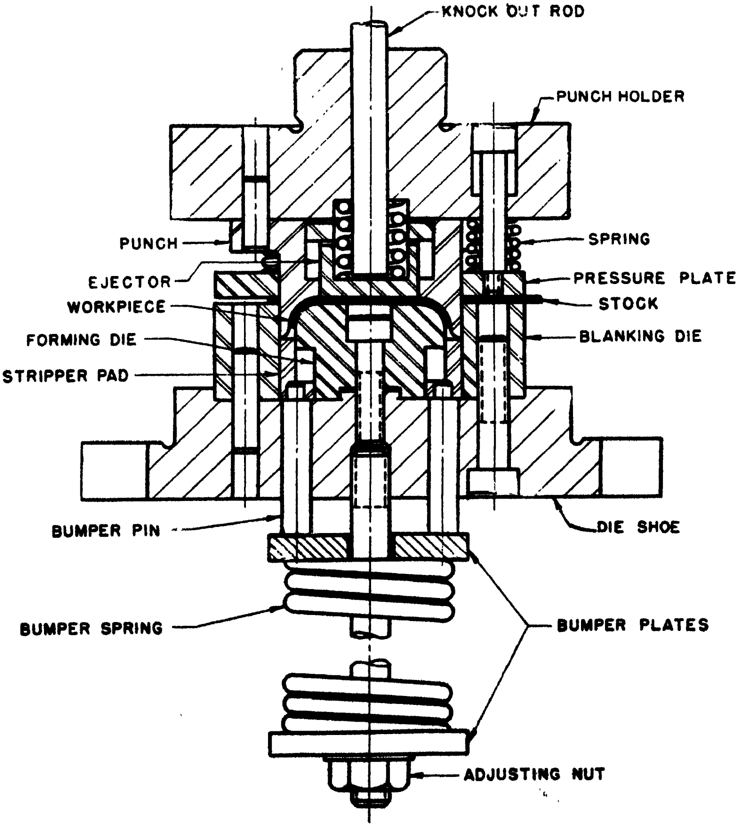

Fig. 199. A cross section of a compound die.

Another designation of gages has to do with those features that determine the way they are applied to the work. A progressive plug gage is shown at the bottom of Fig. 200. The first stage on the plug is supposed to go in in the hole gaged, but the second stage should not enter. Fourth from the bottom, on the right of Fig. 200, is a double-end plug gage. The long plug is the "go" member; the

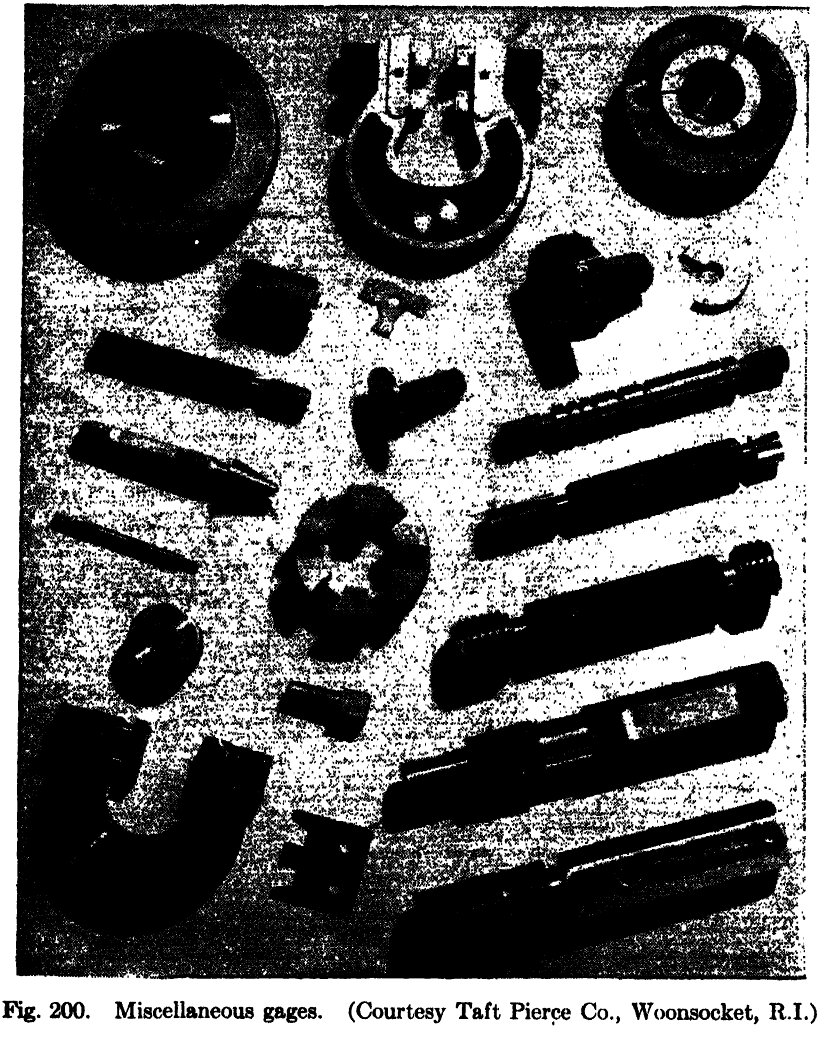

Fig. 200. Miscellaneous gages. (Courtesy Taft Pierce Co., Woonsocket, R.I.)

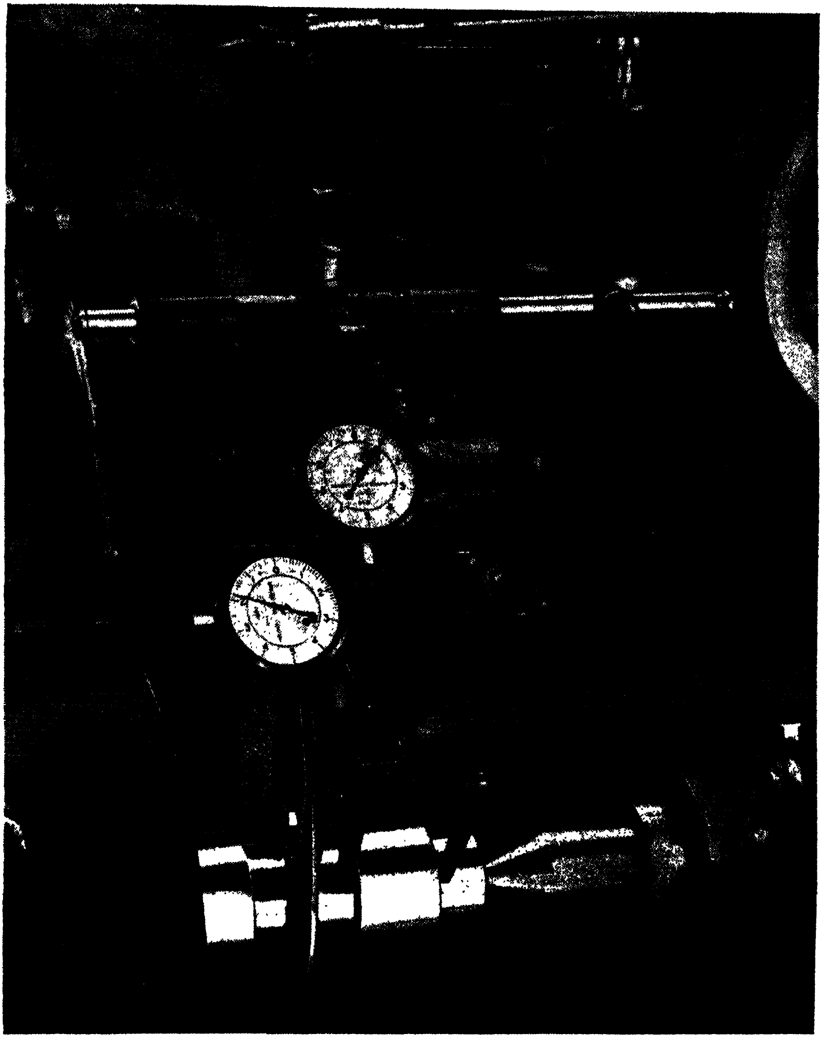

Fig. 201. An easily applied and universally accepted continuous grinding gage for cylindrical center-type grinding. The gage rides the work and reflects dimensional sizes instantaneously, while the piece is being ground. Although the particular instrument is arranged to measure an external diameter and a distance between outside shoulder faces, standard gages of the same type are available for indicating almost any combination of outside surface dimensions.

The outstanding advantage of a gage of this type is that it shows continuously, and instantaneously, the exact dimensions being processed and thus supplants the "feel" of a highly skilled grinder operator in sizing parts. (Courtesy Federal Products Corp., Providence, R.I.)

short plug the "no-go" member. Snap gages and others may differ in a similar way.

One gage may be capable of checking the suitability of a single dimension; another may be used to check several dimensions at once. The latter is called a combination gage. An example is Fig. 189.

Some gages are standard; others special. Plug, ring, snap, and thread gages are obtainable commercially in standard sizes. As a rule, flush pin, receiving, and combination gages are special.

According to accuracy, purpose or use, gages may be classified as working, inspection, and reference gages. A working gage is used by an operator on a machine for gaging the work he is producing. Inspection gages are used to check the work after it has been machined. Reference or master gages are used only for checking the size or condition of other gages. A working gage checks to limits inside of those checked by the inspection gage. Both are usually inside the workpiece dimension limits. The inspection gage is made to less tolerance than the working gage. A master gage is made as nearly as possible to an exact size.

CONSIDERATIONS IN THE DESIGN OF EFFICIENT TOOLS

Economy

Tools must be designed so that they can be *made and operated economically*. Both of these factors must be considered in the design of each tool. The elements of cost in manufacturing, in which tools are used, are described in Chap. 2. The basis for comparing tool costs is developed in Chap. 3. The principles that point the way to achieving economy in tooling are presented in Chap. 4.

The nature of the operation

In every operation, the tools must be adapted to the material, machine, other tools, and operator. To furnish a tool to meet a situation efficiently, the designer must know what the circumstances are and understand what is needed to meet them.

As pointed out in Chap. 11, an important consideration in choosing a standard machine for an operation is the capacity and range of the machine. Once the machine has been selected, the tools used on it must be designed to conform to its dimensions. For instance, a fixture must be securely fastened in place on a milling-machine table. Therefore, it must have a keyway and bolt slots to match the slots in the machine table. The fixture must also hold the pieces so that they conform to the position of the cutter and allow the cutter to be placed near the column for rigidity. The length machined must fall within the travel of the table. Handles, knobs, and levers should be placed on the front of the fixture, convenient for the operator. The feet on a jig must be large enough not to fall into any slots in the drill-press table. A punch and die unit must be proportioned to suit the shut height and stroke of the press. For these and many other considerations, machine-tool specifications, like those of Fig. 157, are used as reference.

A cutting tool must have certain angles and curves to work on the shape of workpiece and kind of material for which it is intended. A stamping punch and a die usually have clearance between them to suit the hardness and thickness of the material. Thus for adequate design of metal cutting and forming tools, an understanding of their action is necessary.

In many metal working operations, large forces must be resisted. These come from the cutting action and from the efforts of the workmen. They cause deflection, which influences accuracy. That will be taken up later in more detail. But in addition, tools must be proportioned to avoid actual destruction and deterioration. Details of fixtures, jigs, and dies must be given enough bulk and backing to stand up under normal cutting forces, clamping and handling forces, and even abuse. To that end, use should be made of the principles of mechanics and resistance of materials in much the same way as is done in the design of most machine members. A consideration of importance in the design of fixtures and jigs is that of providing clamping means to take care of the forces to be resisted. A detailed analysis of that subject is presented in the next chapter.

Accuracy

All operations produce variations in their results. Tool planning determines what variation can be permitted in an operation. The tools to carry out the operation must be designed to keep the variation within the desired limits. Variations arise from errors that result from the following causes:

1. Variations in dimensions of the workpieces coming to an operation.

2. Variations in material condition.
3. Intrinsic defects in tools and machines.
4. Wear.
5. Deflection.
6. Thermal expansion.
7. Dirt, chips, and workpiece mutilation.
8. Errors of human judgment, limits of perception, and deficiencies of skill.

Means of controlling each of these causes of error must be understood by the tool engineer.

Variations in rough workpieces. All dimensions of a workpiece must have tolerances at any stage of manufacture. Rough workpieces have more variation than semi-finished ones, which vary more than finished ones. The amount of variation influences the choice of a locating device, as explained in Chap. 13, and determines the results that may be expected from it. Also, variation in dimensions causes differences in the stock removed from a workpiece with consequent fluctuations in the forces imposed on the tools.

Variations in material condition likewise produce variations in forces and power requirements. Changes in hardness and toughness of work material may often be the primary cause of variation in thermal expansion, deflection, and wear.

Defects in tools and machines are to be expected in all cases, even though they are small. It must be remembered that tool dimensions must have tolerances, too, if their costs are not to be prohibitive. The locating plug, detailed in Fig. 113, has a 1.4998 to 1.4996-in. diameter to suit a hole of 1.5000-in. minimum diameter in a workpiece. Both the variation in workpiece size and the error in tool size are factors that determine the fit between workpiece and locator. Obviously, the smaller the tolerance of a dimension machined in an operation, the closer the locator must be held to keep errors in location within corresponding limits. But the closer the tool tolerance, the more the cost. A satisfactory compromise must be sought to get the work done at the lowest possible cost. Experience indicates what that should be in most cases. For critical dimensions of fixtures, jigs and gages, common practice is to permit tolerances of 5 to 20 per cent (most commonly 10 per cent) of the tolerance to be achieved in an operation. Even so, close tolerances should not be applied indiscriminately. A tool designer needs to be familiar with the normal limitations of toolmaking. If closer performance seems necessary in any case, the designer must investigate its feasibility.

It is customary and economical to use standard commercial cutting tools and details for fixtures, jigs, dies, and gages. The tolerances to which these items are made are published in literature describing the tools. That information is useful in putting these standard items into a design and in fixing the specifications of special tools similar to the standard ones.

Since any tool detail cannot be made to an exact size and is subject to wear, as few parts as possible should be used for any locating device to keep down the accumulation of errors.

Different designs for a specific purpose may give different degrees of accuracy. Conventional chucking devices and modifications furnish an example. For turning and boring, the three-jaw universal scroll chuck offers wide adjustments, versatility, rapidity of operation, heavy gripping power, and ruggedness. Because of the number of parts it contains, all having errors, this type of chuck cannot always be expected to locate a workpiece accurately. High-grade chucks are guaranteed to have an initial runout not over 0.003-in. total indicator reading. That accuracy can be kept for a long time if the chucks are used carefully. But too often they are abused. In one place about 25 chucks that were in use were checked for runout, and the best showed a runout of 0.007 in. total indicator reading. For rough surfaces a runout of 0.010 in. or more is acceptable, and serrated jaws for biting into the work material are usually placed on the three jaw chuck as indicated in Fig. 202A.

For gripping semi-finished or finished surfaces, smooth soft jaws are applied to the universal three-jaw scroll chuck and for accuracy are turned or bored in place under gripping pressure, as depicted in Fig. 202B. According to the Warner and Swasey Co.,[3] workpieces can be held to a concentricity of 0.002 in. with a previously machined chucking surface by this means. For long runs, it may be necessary to retrue the soft jaws occasionally as they wear.

For accuracy closer than 0.002 in. on the scroll chuck, the actual function of location is taken from the jaws, which are left only with

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[3] J. R. Longstreet, and W. K. Bailey, *Turret Lathe Operator's Manual*, page 129. Cleveland, Ohio: The Warner and Swasey Co., 1940.

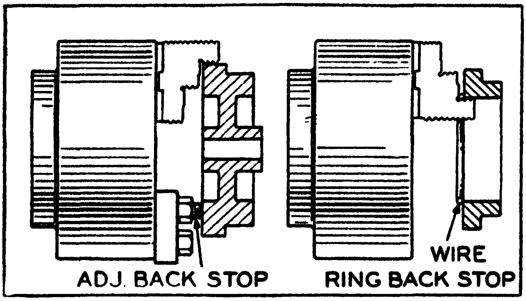


Fig. 202A

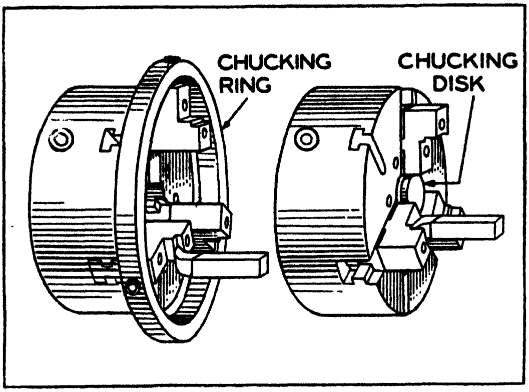


Fig. 202B.

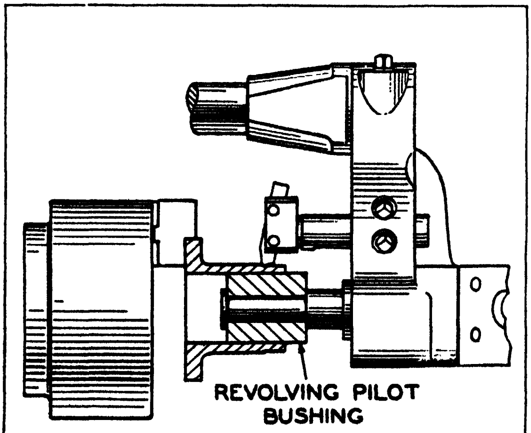
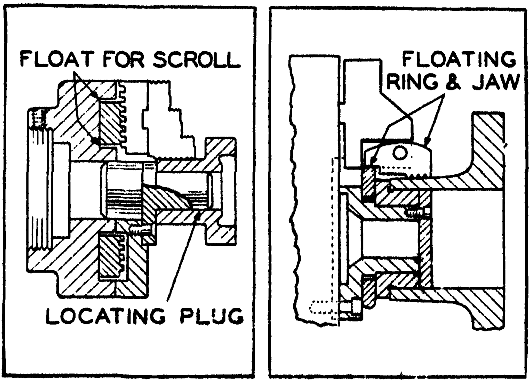


Fig. 202C.



Figs. 202D and E

Fig. 202. Chucking arrangements of various degrees of accuracy. (A) Standard hardened and serrated reversible top jaws and back stops applied to universal chucks. For clarity, only one jaw is shown on each chuck. (B) For accuracy, soft jaws are applied to a universal chuck and turned or bored under gripping pressure. Such jaws may also be hardened and ground in position under gripping pressure. (C) Workpiece held in soft jaws and tool guided by revolving pilot for accurate concentricity. (D and E) Workpieces located on plugs. (Courtesy Warner & Swasey Co., Cleveland.)

that of gripping. One arrangement, shown in Fig. 202C, has the piece held in the jaws, but the tool guided in relation to an internal bore by a revolving pilot. A plug mounted on the chuck body may be the locator, as shown in Fig. 202D and E. The plug is indicated, finish-turned, or ground in place for truth. The concentricity attained depends upon the fit between the plug and the workpiece. The jaws float so that they grip firmly with compensated pressures on the piece located by the plug in the center hole.

For closer confinement other types of chucks are available in which range, versatility, and to some extent holding power are sacrificed. One of these is the sliding-jaw chuck, illustrated in Fig. 203B. The sliding jaws are held under gripping pressure by a spider, while the removable jaws are bored or ground in position to the size of the workpiece surface to be gripped. A concentricity of 0.001 in. T.I.R. is possible with this type of chuck. Another type of chuck, however, known as the diaphragm chuck, is shown in Fig. 203C. The jaws on this chuck likewise are ground in posi-

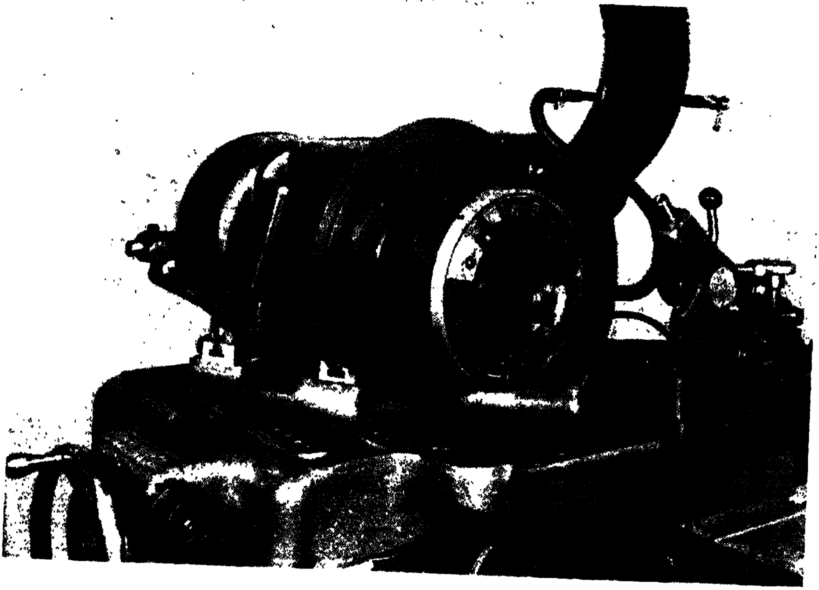


Fig. 203A

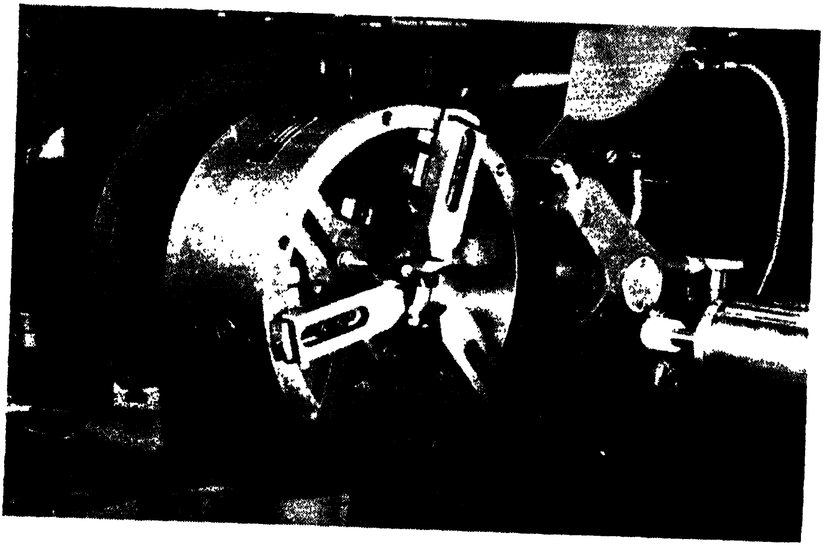
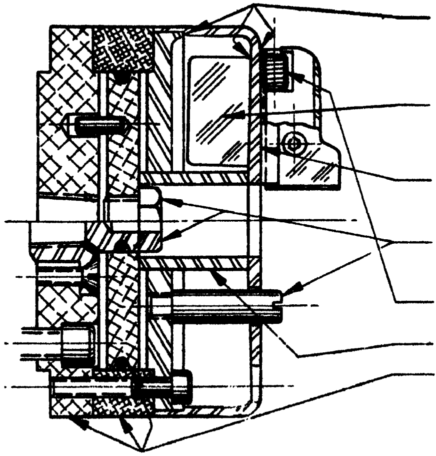


Fig. 203B



(1) Diaphragm, Jawbase, Backplate and Counterweights *hydrogen-welded into integral unit* for strength, lightness and compactness.

(2) *Counterweights* counteract centrifugal force of Jaws, thus permitting high speeds, suitable for diamond boring.

(3) *Cup shaped diaphragm* is not dependent on pilot fit and can deflect without losing location.

(4) *Work Stop*, either *receding* with piston *or fixed* solid in adapter plate.

(5) *Jaws are rigidly mounted, yet adjustable.*

(6) *Diaphragm* assembly is *chip proof.*

(7) Built-in cylinder, piston and adapter plate are of aluminum alloy for *lightness and strength.*

Fig. 203C

Fig. 203. Chucking arrangements for greater accuracy. (A) A collet chuck. (B) A sliding jaw chuck. The permanent jaws slide on accurate wedges and have adjustable jaws fastened to them. The latter can be set to approximate size and ground in position. (Courtesy of Bryant Chucking Grinder Co., Springfield, Vt.) (C) A cross section of a diaphragm chuck. (Courtesy N. A. Woodworth Co., Detroit.)

tion under pressure for accuracy. The manufacturer guarantees concentricity of 0.0005 in. T.I.R. if the workpiece chucking diameter is held to 0.002 in. tolerance and a concentricity of 0.0002 in. T.I.R. if the chucking diameter is within 0.0005 in.

Although errors must be expected in all constructions, much can be done by positive measures to impart accuracy to tools. Details of fixtures, jigs, dies, and gages that require accurate location should be held by dowels, splines, or keys, in addition to screws. Screws should not have to perform the double function of locating and holding. The fixed V-blocks of the jigs of Figs. 168 and 170 are held by screws and located by dowels.

Where several pieces are to be placed in a fixture or jig, they should not be located one against the other. If that is done, ultimate location depends upon the accumulated accuracy of the pieces, which is not as close as that of the tool. Rather. the workpieces should be located independently, although several or all may be clamped by one motion.

The jig leaf of Fig. 170 is guided at both ends so that positioning it is not left entirely to the hinge. In any event, hinge pins of the sort shown in Fig. 170 should be a tight fit in the inner member and loose, for turning, in the outer member. That results in the least freedom for the leaf. Clamping of the workpiece in the jig is done entirely by the tapered V-blocks. If clamps were to be placed in the leaf, they might tend to spring it and impair the locations of the bushings. The support for the leaf in the open position protects the leaf from abuse and consequent misalignment when it is thrown back. That is a measure to preserve the accuracy of the jig.

One or more tools may be held in a block on an automatic lathe slide. For rough operations, with tolerances of 0.010 in. and over, such tools can be set in place on the machine with the aid of common measuring instruments. To make the setting easier and more accurate, a gage may be supplied for the tool block. More accurate results may be obtained by making the tool block removable. The block may locate in a dovetail way against a stop. When the tools in one block become dull, the block is removed from the machine and replaced by a spare having sharpened tools already positioned. The tool holder containing the dull tools is sent to the grinding room, where the tools are removed from the holder, sharpened to template, reset in the holder to gage, and returned to the machine. Tools are commonly preset in this manner and perform consistently on jobs holding tolerances of ±0.001 in. and less.[4]

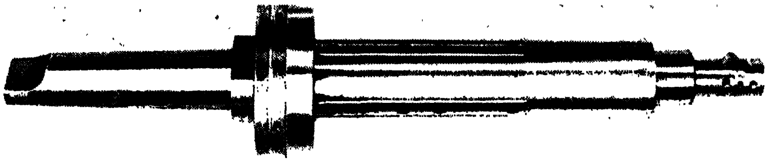


Fig. 204. A precision boring bar with hard nonferrous strips. Wear on the guiding surface or pilot is reduced and the life of the bar is lengthened by this application. (Courtesy Scully Jones & Co., Chicago.)

Wear inevitably adds to the variations experienced over a period of time. It is usually desirable to insert wear-resistant materials in areas subject to wear on fixtures, jigs, and gages. Where comparatively large details are needed, it is desirable to use low-cost machine steel, carburized and hardened. More expensive materials are commonly inserted at critical spots where their use is advantageous. The indexing device of Fig. 197 has hardened tool steel inserts where wear may occur. Figure 204 shows a precision-boring bar, with its pilot diameter reinforced for wear resistance by cast nonferrous alloy strips.

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[4] *Tool Holders and Tool Setting Devices—Data Sheet.* Detroit, Mich.: Carboloy Co., Inc., 1941.

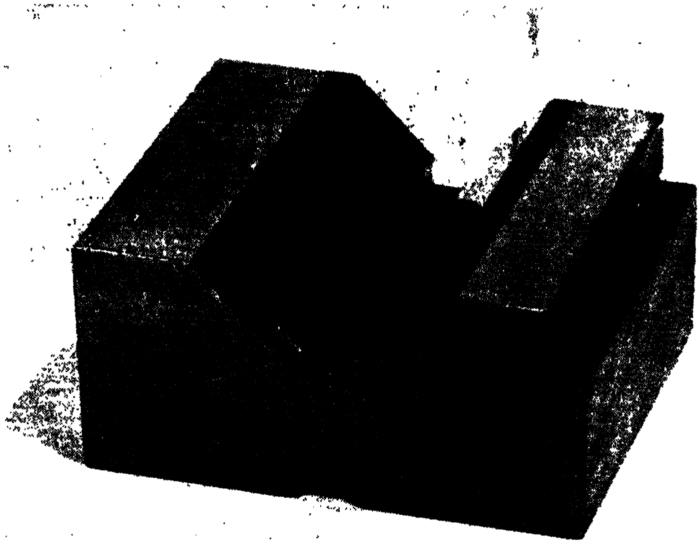

Fig. 205. Extremely hard sapphire wear-strips inserted in and bonded to a steel block to make a wear-resistant V-locator. (Courtesy Sapphire Products Div., Elgin National Watch Co., Elgin, Ill.)

Figure 205 shows sapphire strips inserted and bonded in place to form the surfaces of a V-locator. Application of this material to tools and gages have been reported with a useful life 7000 times that of steel.

An indication of the wear resistant properties of common materials subject to rubbing or abrasion is given by Table 7.

TABLE 7

WEAR RESISTANCE OF TOOL MATERIALS TO DIRECT ABRASION*

Surface Material	*Ratio of Wear in Terms of Amount of Metal Removed in a Given Time*
Heavy metal carbides (tungsten or titanium carbide)	1
Hard nonferrous alloys (like Stellite)	15
Hardened alloy steel	25
Hardened plain carbide steel (or case hardened steel)	40

* Reported by E. E. LeVan, "Wear of Metallic Surfaces," *Metals and Alloys*, July 1937, Vol. 8, No. 7, page 206.

Wearing surfaces should be as small as possible without sacrifice of too much durability. The benefits gained from small locating surfaces are: (1) less time for cleaning, (2) a reduced chance for lodgment of disturbing particles, (3) a more realistic approach to the mean plane of a rough surface, (4) some saving in material and labor. Offsetting these benefits is the greater rate of wear, causing higher tool maintenance costs.

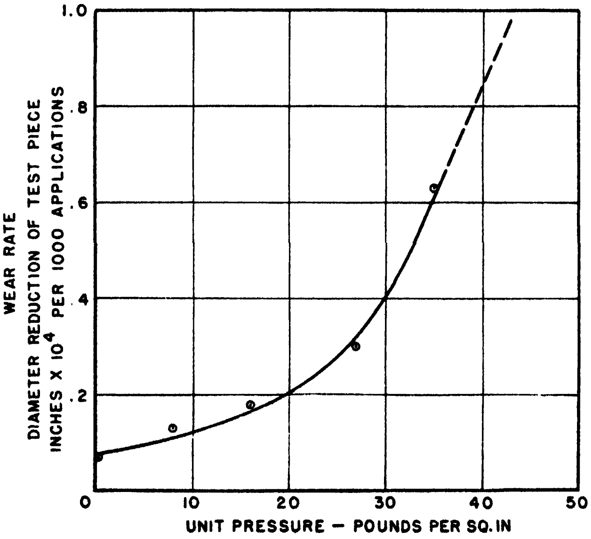

Fig. 206. Wear of a hard steel plug subjected to metal contact with a hard steel split ring under various pressures. (Reported by French and Herschman, "Wear of Steels with Particular Reference to Plug Gages," *Trans. ASST*, Vol. 10, 1926.)

The optimum area is that which provides the most economical balance between savings and impairment. As the area decreases under a given load, the pressure increases. Under high pressures the rate of wear increases rapidly. A clue to economical conditions is given by the curve of Fig. 206. That curve applies strictly to the conditions of the tests for which it stands. It does indicate, though, that for pressures under 25 lb/in.^{2}, there is likely to be little difference in the rate of wear. This conforms to practical experience. In the standard practice of one large plant, pressures up to 25 lb/in.^{2} are allowed for bearing and contact surfaces.

The forces acting on the locating surface, that arise from normal loading, should be considered. They may be the weight of the part or the direct manual effort exerted by the operator. It is not desirable that actual clamping should produce sliding over the locators, as that causes unnecessary and excessive wear.

Example 25: A process for machining the bracket of Fig. 5 includes milling the large face with the integral key. It is desired to rest on the rough underside of the section, to secure uniform thickness, on three buttons $\frac{1}{2}$ in. in diameter. What will be the pressure on these locators, and will it be excessive?

As workpieces are placed on the buttons and slid into place, wear will be imposed mostly by the weight of the workpiece, about 5 lb. The average force sustained by each button is $1\frac{2}{3}$ lb. The area of each button is $\pi/16$ in.^{2} The pressure on each button is

$$\frac{5/3}{\pi/16} = 8.5 \text{ lb/in.}^2$$

This pressure should not impose a rate of wear appreciably greater than would take place if the locating surface were to underlie all of the available section of the workpiece.

The longer the bearing between a drill and a bushing in a jig, the more the wear. The length of bearing for the drill should, in fixed bushings, be about $1\frac{1}{2}$ to 2 times the diameter of the drill; in slip bushings about 2 to 3 times. More bearing than this does not add much to accuracy, and any excess length within the bushing should be relieved to keep down wear.

If drill bushings are brought close to the workpiece, the chips must pass through the bushings. This increases wear, but in some cases that disadvantage is tolerated because the drill is located nearer to the work, and chips are carried out of the jig where they are disposed of more easily.

As cutting tools and dies wear, the results they produce change. Form tools, particularly, change in shape and size. It is customary to dimension such tools to leave the most possible material on them for wear. Wear resistant materials, like cemented carbides, have been widely adopted for cutting tools because of the longer periods over which they produce accurate results. A typical report[5] on machining heat-treated steel shafts showed 1284 in.^{3} of metal removed per grind by cemented-carbide tools as compared with 160 in.^{3} per grind for high-speed steel tools, at a cost of $1.42 per shaft in the first case as against $3.19 in the second.

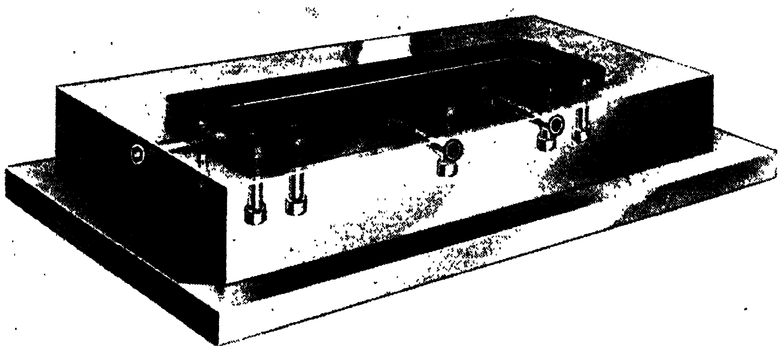

Fig. 207. A die block with wear-resistant cemented-carbide inserts. (Courtesy Carboloy Co., Inc., Detroit.)

Figure 207 shows how a die block may be made with cemented-carbide inserts. Although a cemented-carbide blanking or piercing die does not produce a better product than a similar, properly designed steel die during the first part of its run, the cemented-carbide die has been found able to continue giving the same quality over extremely long runs. A leading manufacturer of cemented carbide die inserts reports for stamping a life of 20 to 40 times and for forming a life of 10 to 30 times, and even as high as 75 times, as much as for high-speed steel dies.

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[5] Cyril Donaldson, and George H. LeCain, *Tool Design*, page 153. New York: Harper and Bros., 1943.

Tools often have *parts that move in relation to each other.* Machine tools particularly, have such surfaces in the forms of bearings and ways. Normally, uniform wear of such surfaces is not deleterious if not excessive, but localized wear generally is damaging. Impairment may result from concentrations of pressures in small areas, from lack of guards or covers to keep chips and abrasive particles from the surfaces, from lack of lubrication, or from actual mistreatment. Provisions must be made to avoid these situations as much as possible. The indexing device of Fig. 197 has dust shields to prevent the entrance of foreign particles and means for lubricating the bearings.

An allowance for wear is often given to "go" work and inspection gages, since they receive more wear. The wear allowance is added to and taken on the same side as the gagemaker's tolerance, to make the total tolerance of the "go" gage.

Deflection is always present where forces of any size bear upon physical objects. To a certain extent forces can be predicted and deflection anticipated in tools. But variations in materials, speeds, feeds, and other factors bring about changes in deflection that result in variations in the results obtained. A dull cutting tool, for instance, may give rise to several times the force of a sharp one. Deflection can never be eliminated, but it can be reduced to minor proportions. It follows that if deflections are small, variations in them will be correspondingly smaller.

Forces causing deflection may come from handling, clamping, or cutting action. A gage is deflected if it is forced over a workpiece. A workpiece in a fixture or jig may be deflected by cutting forces if it is not adequately supported. Clamping forces may distort a fixture if it is not rugged enough. Tools must be designed for a minimum of deflection in their own members. They must also give adequate support to the work.

Positive measures must be taken to protect against deflection. Little can be done oftentimes to alter the character of a workpiece if it is frail and deflects easily under necessary cutting and clamping forces, but proper precautions can be adopted to overcome any such condition. In the first place, clamps should never be applied to an overhanging section of a workpiece but, instead, should bear directly over fixed locating rests or stops, if possible. If those facilities are lacking, clamping forces should be opposed by adjustable supports.

An example of a commonly used form of adjustable support, known as a jack support, is shown in Fig. 208. A fixture having two jack supports is in Fig. 65.

It is important that devices employed as reinforcements against deflection do not themselves introduce additional deflection. A suitable adjustable support must not be capable of performing its function because of the initial force it may exert but rather because it is not reversible. Adequate precautions include means of preventing an operator from exerting excessive force in applying the support. An example of this principle is in Fig. 209. The support screw can be brought up too strongly by the operator and may distort the workpiece. The machined face is thus thrown out of line when the flange springs back after the piece is released. In this case, a support screw with a nonreversing thread and a torque-limiting device built into its head may be used. Another satisfactory device has the support brought up to the work only by a light spring, and the

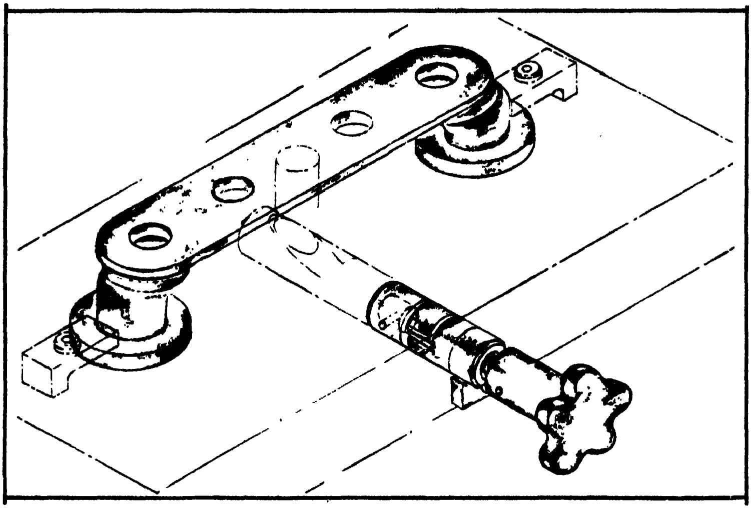

Fig. 208. An example of the use of a jack support. The top surface of the casting is supported against deflection when milled by the adjustable post that makes contact with the underside of the workpiece without springing it upward. At the same time, the support is locked to prevent its giving under load. (Courtesy N. A. Woodworth Co., Detroit.)

operator just locks the support in place without adding to the force put on the work.

Supports should directly oppose forces. Quite often deflection and accompanying vibration or chatter can be limited to desirable amounts only by a restriction of production rates. In a machining operation, it is not unusual that, to control deflection, the speed and feed may have to be held below what the machine and cutters will stand economically. The remedy is found in better tooling. Figure 210 illustrates such a case. In view *A* the workpiece is shown as it was held originally, firmly secured to the table, but lacking support near the surface where the facing cut was taken. Later a fixture was furnished, as shown in *B*, to reinforce the workpiece, and allowed a higher rate of production, sufficient to pay its cost from the savings realized from only a few parts.

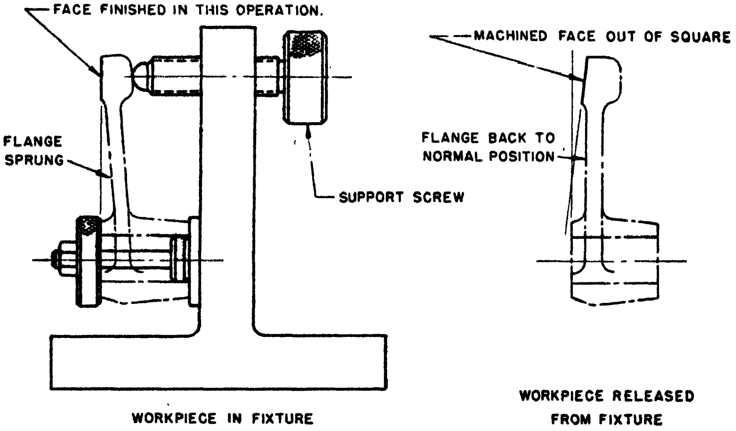
FACE FINISHED IN THIS OPERATION.
MACHINED FACE OUT OF SQUARE
FLANGE SPRUNG
FLANGE BACK TO NORMAL POSITION
SUPPORT SCREW
WORKPIECE IN FIXTURE
WORKPIECE RELEASED FROM FIXTURE

Fig. 209. How an improperly applied support deflects a workpiece. The machined face is thrown out of line when the piece is released from the fixture and the flange returns to its normal position.

In the form of a general principle, it may be said that it is desirable to place the cutting zone as close to the machine table as possible. However, if circumstances dictate that the forces must act some distance above the table, then the surface taking the thrust must be adequately reinforced, as nearly as possible in line with the cut.

Adequate holding devices are arranged so that deflection inducing forces are transmitted to rigid basic members. All clamping strain should be taken care of within a fixture. None of it should be transmitted to the table of the machine. The provision of sufficient material properly proportioned to limit deflection is an important consideration for tools.

Thermal expansion may be appreciable when considerable energy is dissipated into heat in a manufacturing operation. The effect upon accuracy of large expansions and contractions is obvious. But even small temperature changes may determine the accuracy obtainable in precision work. The jig boring machine of Fig. 100 is a highly sensitive instrument. A skillful operator can space two holes to within one or two ten-thousandths of an inch. But the drilling and boring of the holes introduces heat. A rise in the temperature of the workpiece of 10° is not unusual. In a distance of 10 in., an expansion of 0.0006 in. in iron or steel takes place and adds an appreciable error to the results.

Fig. 210A

The results of thermal expansion are most pronounced where dissimilar metals are involved. Steel has a coefficient of expansion of 6.36×10^{-6} in./in./F°, and aluminum 1.234×10^{-5} in./in./F°.

Thus, for each degree change in temperature, aluminum expands approximately twice as much as steel. Aluminum pieces 100 in. long are not uncommon in aircraft structures. Such a piece, having a hole near each end, expands about 0.025 in. between the holes for a 20° rise in temperature. In contrast, a steel jig for these holes expands only about 0.013 in. for the same temperature rise. A limit of accuracy is clearly discernible if various pieces of the same kind are drilled at different temperatures.

The most effective manner of minimizing the effects of thermal

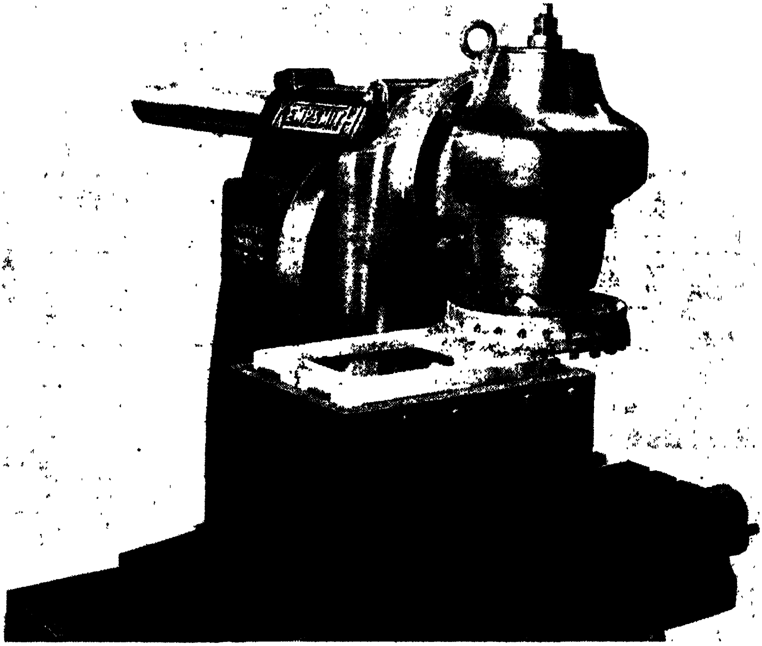

Fig. 210B

Fig. 210. A gear case being face milled. View (A) shows the sort of setup often found on what might be regarded as production work. Setup time is high, and adequate work support is lacking.

In view (B) the same operation is being performed with the aid of a simple, yet effective, fixture which provides support for the workpiece near the surface where the cutting forces are applied. Setup time is shorter and a faster feed can be utilized. Although in the particular instance only a relatively small number of castings were to be milled, the fixture more than paid for itself on the first few castings. (Courtesy Kempsmith Machine Co., Milwaukee.)

expansion is to moderate the temperature differential. Circumstances by which temperature may be controlled are:

1. The employment of sharp tools of proper shape, which require a minimum of energy and produce less heat.
2. Provisions for adequate heat dissipation from tools and machines. For instance, any situation should be avoided where chips are allowed to cover hot oil manifolds or lines in a hydraulic system.
3. Uniformity of power consumption. If a workpiece moves through several stations, an overload of work at any one station may produce an undesirable rise of temperature in the workpiece at that station.
4. An ample supply of coolant. An important function of a cutting fluid is to cool workpiece and tools. Provision should be made so the fluid can be applied easily and gain access to all areas.
5. Controlled room temperatures. Air is often held at constant temperatures in plants fabricating aluminum and magnesium.

Dirt, chips, and burrs interfere decidedly with workpiece location, positioning, and gaging. Every possible precaution should be taken in the design of tools to reduce the affect of such disturbances.

A fundamental rule of tool design is that locating surfaces should be as small as is consistent with durability. The smaller the area, the easier it is to clean. Hardened blocks and buttons are commonly inserted in fixtures and jigs for this reason.

Sharp corners should be avoided between locating surfaces. They catch dust and dirt and are hard to clean. Grooves like those in Fig. 211 act as vents for small unwanted particles and clear burrs on the workpiece.

Locating surfaces should be elevated above surrounding surfaces so that particles can fall clear of their own accord. Also, ample space around the locators makes it easier to remove chips from the vicinity. Pockets where chips can accumulate should be avoided. If possible, chips should fall away from, rather than on to, the locating surface when the work is removed. It is desirable to keep locators completely covered by the work, so that chips cannot collect on any part of them.

Access to locators should be free for cleaning and observation.

Cross grooves with sharp edges may be put in rest plates. The edges scrape and clean a workpiece surface as it is moved over the plate.

An example of good design with respect to chip control, as well as in other respects, is shown in Fig. 198.

When a cutting fluid is used in a machining operation, consideration should be given to means of directing it most efficiently toward washing the working area free of chips and dirt. Ample passage also should be provided to enable the cutting fluid to carry the refuse from the working zone. Figures 231 and 53 illustrate such means.

When the use of fluid is not desirable in an operation, jets of compressed air may be applied to blow unwanted particles from locating surfaces. Such an installation is shown in Fig. 32.

Dirt and chips may interfere with the operation of and cause wear in a mechanism if they are not kept out. For dependable service, it is well to shield mechanisms, like the indexing device of Fig. 197.

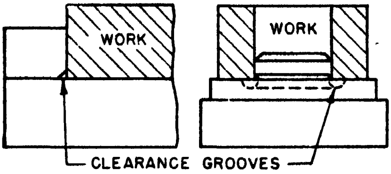

Fig. 211. Examples of relief grooves to clear chips, dirt, and burrs.

Distortion and permanent deformation, scratching, scoring, and nicking are among the chief causes of mutilation of workpieces. In themselves, these defects are common grounds for rejection but they also contribute to impairing locating surfaces and increasing errors. Where they are likely to occur, they must be anticipated. For instance, it is good practice to use soft jaws, sometimes tipped with brass or copper, for chucking on finished surfaces. It may often be desirable to supply special containers, racks, or other safeguards for workpieces after surfaces on them have been finished.

Errors due to limits of skill, inattention, fatigue, and inability to see closely are inherent to some extent in every human endeavor. Many devices have been developed to mitigate the effects of human deficiencies. Tools may be refined to almost any degree to make up for the operators' shortcomings. As an illustration, consider a tool brought up to face a shoulder on a workpiece in production. This may be done[6] by experienced operators positioning the carriage of a turret lathe against a standard fixed stop to limits of ±0.001 in. However, when closer limits must be held in production, indicators, dial stops, or special micrometer stops are necessary to aid the operator in bringing the carriage manually to position. For greater precision, hydraulic devices can be arranged to position a tool consistently with less error than is discernible on a dial-indicator gage.

In precision cylindrical grinding, a skilled operator can manipulate the crossfeed handwheel to a definite stop to produce a dimension to within 0.001 in. in production. Hydraulic grinders on which the grinding wheel is brought to position automatically, without exercise of exceptional skill on the part of the operator, regularly turn out work to tolerances of less than 0.0005 in. The addition of a grinding gage, like that of Fig. 201, makes performance possible to 0.0001 to 0.0002 in. consistently.

The workpiece of Fig. 189 may be inspected in a number of ways. Several require skill, like the use of a sine bar. One solution to the problem of checking the piece easily and quickly is the special combination gage shown in Fig. 189.

A basic purpose of all tools is to provide means of achieving accuracy with the least skill and effort. The extent to which any tool is refined for that purpose depends upon the accuracy required and the expense justified.

SUMMARY

The purpose of tool design is to devise and proportion the tools to carry out the production plans most efficiently. To do that, the following steps are taken.

1. Determine what the tool must do and under what limitations it must perform.
2. Select or devise the form of the tool to meet the requirements.
3. Arrange and proportion the tool to do the job most efficiently.

For the second step, an acquaintance with the various types of tools is necessary. For the third step, consideration must be given to what will provide:

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[6] J. R. Longstreet, and W. K. Bailey, *Turret Lathe Operator's Manual*, page 26. Cleveland, Ohio: The Warner and Swasey Co., 1940.

a. Economy.
b. Adaptability to the operation.
c. Accuracy.

For economy, tools must be designed so that they can be both made and operated at the lowest cost and still meet requirements. This permeates all other considerations.

Tools must be proportioned for the kind of material they are to act upon; the shape of the workpiece; to suit the size, range, and capacity of the machine; to fit in with other tools; and to help the operator.

For accuracy, the causes of errors must be considered. Errors in an operation arise from:

1. Variations in the sizes of rough workpieces.
2. Variations in materials.
3. Intrinsic defects in machines and tools.
4. Wear.
5. Deflection.
6. Thermal expansion.
7. Dirt, chips, and workpiece mutilation.
8. Human deficiencies.

Sometimes allowances must be made for unavoidable errors, but often positive measures can be taken in well-designed tools to minimize the effects of each of the causes of error.

QUESTIONS

1. What is the responsibility of tool design?

2. Define a tool. What does the term tool include?

3. How may a tool design department be organized?

4. What three steps are involved in the design of any tool?

5. What three main considerations are involved in proportioning a tool?

6. What are machine tools? What contact does the tool designer have with them?

7. Define a fixture. How may fixtures be classified? What are some of the common types?

8. Define a jig. How are jigs usually classified? What are some common types?

9. What are cutting tools? How may they be classified?

10. Why should standard cutting tools be used wherever possible?

11. What kinds of dies are used for cutting metal? For shaping metal? Describe them.

12. What kinds of dies perform more than one operation at the same time?

13. Define a gage. Why are gages used?

14. Name and describe the principal types of gages.

15. How may gages be classified according to accuracy, purpose, or use?

16. What two considerations enter into tool economy?

17. To conform to what factors in an operation must a tool be designed? Give examples.

18. What are the causes of error in manufacturing?

19. How may tools serve to reduce manufacturing errors?

20. How do variations in rough workpieces cause variations in results?

21. How do variations in material condition affect manufacturing tolerances?

22. What two factors determine the fit between a workpiece and locator?

23. What part of the tolerance to be achieved in an operation is usually given to critical tool dimensions?

24. How may reference to published tolerances of standard tools and details be helpful to the tool designer?

25. Explain how differences in design may affect accuracy.

26. Are mechanical linkages desirable for locators? Why?

27. Describe positive measures which may be taken in the design of tools to insure accuracy over a long life.

28. How may wear in tools be kept down?

29. What are common wear-resistant materials?

30. What is done to economize on wear-resistant materials?

31. What is the relative resistance to wear offered by the common materials used for that purpose?

32. What benefits are gained from small locating surfaces?

33. What determines the size of a locating surface?

34. What range of pressures are satisfactory for locating surfaces?

35. How are drill jig bushings designed to minimize wear? Is more than minimum wear ever tolerated? Why?

36. How may wear be reduced in cutting tools and dies?

37. What form of wear is most damaging to tools?

38. What provisions may be made to keep down wear in a mechanism?

39. What forces may cause deflection in manufacturing operations?

40. What positive measures may be taken in the design of tools to protect against too much deflection?

41. What may be done to reinforce weak workpieces?

42. What precautions must be taken in applying supports to workpieces?

43. Where should reinforcements against cutting forces be placed?

44. Under what conditions are the effects of thermal expansion most pronounced?

45. How may temperature changes be kept down?

46. How can locators be arranged to minimize the effects of dirt, chips, and burrs?

47. How can cutting fluid or compressed air be used to cut down the effects of external disturbances?

48. What may be done to allay operators' shortcomings?

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15 CLAMPING PRINCIPLES

An outline of clamping considerations

The purposes of clamping are to bring a workpiece firmly against the points and surfaces that locate it and to hold it there securely against all disturbing forces. To fulfill these purposes, a clamp must direct and maintain a force. The choice of a clamp to do this effectively involves a series of considerations. They are:

1. The sizes of clamping forces needed for a particular application; where they must and can be applied; in what directions they should act. The chief factors affecting this decision are:
    a. The type of locator and the positions of the locating surfaces.
    b. The ruggedness or frailty of the workpiece.
    c. The surface or surfaces available for contact.
    d. The condition of surfaces on which forces are to be imposed.
    e. The directions and sizes of the cutting forces to be opposed.
2. The economy of clamping, which involves a choice on the basis of:
    a. The mechanisms available.
    b. The advantages of complicated and quick acting devices as compared to simpler but slower ones.
    c. The feasibility of combinations.
3. The source and size of the force available for actuating the clamp.
4. The proportions of a clamping device to enable it to put forth a desired force and to resist excessive reactions.

Each of these considerations is governed by certain principles. Under the limitation of our present incomplete knowledge of the subject, the application of these principles cannot always be precise, and the exercise of judgment is more often than not necessary to arrive at a workable compromise. But for either course, an understanding of the principles is necessary for guidance.

THE FACTORS AFFECTING THE POSITIONS, DIRECTIONS, AND SIZES OF CLAMPING FORCES

The nature of the locating surfaces

Locating and clamping are two different concerns. They are related only to the extent that the choice of clamping means is partly influenced by location. The latter should not be governed by the former. It would be a mistake to try to select first an attractive clamping device for a jig or fixture and then to fix the locating points entirely from the standpoint of how well they match the clamping

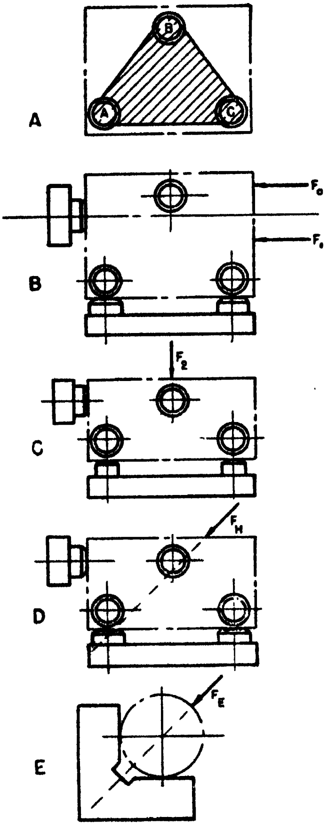


Fig. 212. How clamping forces must act with respect to locators.

(A) The locating points are A, B, and C. The component of the clamping force normal to the plane should pass through the shaded area.

(B) The force F_0 creates an unopposed moment and should be avoided. The correct application is the force F_1 acting between the locators.

(C) The force F_2 must be within the zone shown for stability.

(D) Extension of the line of action of a single horizontal clamping force, F_H, must pass between outside locating points.

(E) F_E must pass between the two points of contact to secure the part in the V.

method. The locating decision must be made on the basis of the most effective way to position the surfaces to be worked in an operation. Then clamping enters to give stability to the location.

Obviously, a clamping effort must be directed so that it does not upset the location of the piece on which it acts. This places initial restrictions upon the direction and position of every clamping force. Thus, if a piece is located on three spots in a horizontal plane, as indicated in Fig. 212A, only a vertical force, or component, can press the piece against the locators. If the points are *A*, *B*, and *C*, the vertical clamping force must pass within the shaded triangular area to avoid tipping.

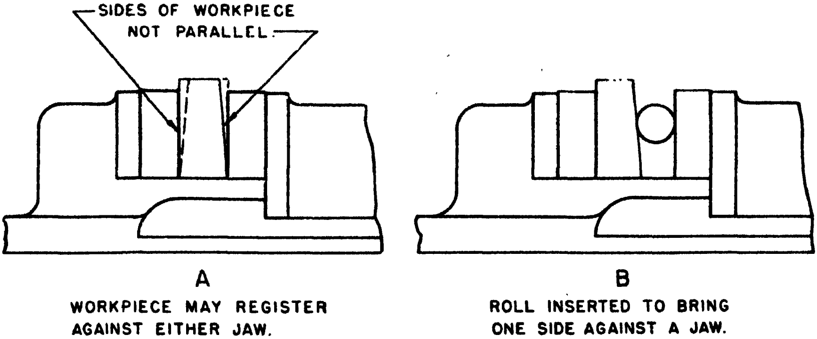

SIDES OF WORKPIECE NOT PARALLEL
A
WORKPIECE MAY REGISTER AGAINST EITHER JAW.
B
ROLL INSERTED TO BRING ONE SIDE AGAINST A JAW.

Fig. 213. A Piece with nonparallel sides clamped in a vise.

A common example of the difficulty that may ensue from neglect of the principle of directing a clamping force within the locating area is given by a piece held on untrue sides in a vise, as indicated in Fig. 213A. Such a piece between plain vise jaws may register against either jaw. Positive location against the fixed jaw, the more accurate, is a matter of chance unless the movable jaw is relieved or a roll is inserted to bring the clamping force well inside the edges, like in Fig. 213B.

Where a clamping force cannot be brought to bear directly on top of a piece, it may have to be arranged to act with a downward component. The swinging pinch clamp of Fig. 215 should be made to touch the workpiece only after it has passed the top of its travel, so that it pulls down as it presses against the work.

A horizontal clamping force, acting in the direction of a single end stop, like in Fig. 212B, must not bear, like F_0, in such a way as to set up a moment away from the other locators. Instead, it should act like F_1, between the locators. Likewise, a component like F_2 in view *C* must pass between the two locators that oppose it. If two horizontal clamping forces are combined into one, acting like F_H in Fig. 212D, it must pass between the two extreme locating points. It follows, too, that a force F_E, in Fig. 212E, must act between the points of contact of workpiece and V to be effective. In Figs. 168 and 170 that is done.

The strength of the workpiece

A force acting within a locating area, such as the shaded area of Fig. 212A, must be further restricted so that it does not deform the workpiece. If a piece is heavy and strong, it may be possible to clamp it anywhere without fear of distortion. However, care must be taken to avoid clamping on weak sections without proper support. In general, clamping forces should bear upon heavy sections directly supported by fixed locators, wherever possible.

In Fig. 142 the small cylinder blocks are held down by strap clamps bearing on top of each block. The sections of a block are sufficiently heavy to transmit the forces to the locating surface that underlies the entire finished bottom surface. Another cylinder block, shown in Fig. 141, is clamped by a similar device, this time bearing directly on the locating flange, but still within the locating area.

The large cylinder block shown in Fig. 143 rests on locators at the ends of the bottom surface. The strap clamps are applied directly over the locators.

In spite of all that can be done, there are times when the fixed locators are not adequate to support a piece as it should be against the clamping forces. Circumstances may make it necessary to apply the clamping forces outside of the locating area, to apply them where they may cause distortion even though they fall within the locating area, or to apply the forces on sections that are likely to deflect even though they are above fixed supports. For instance, the flange of the casting, outlined in the fixture of Fig. 65, is located on four buttons, but the section there is strong enough so that the clamp may be placed between the buttons. However, the end to be milled must be held down also. An unopposed clamp so far from the bearing surface could undoubtedly be expected to distort the piece. To avoid distortion, an adjustable support is provided under the overhanging section. Adjustable supports are also used to resist deformation from cutting forces.

The availability of clamping surfaces

The most natural surfaces for clamping may not always be available for that purpose, necessitating recourse to others less desirable. Normally, surfaces that are machined in an operation are not accessible also for clamping. For instance, the piece in the fixture of Fig. 214 has most of its top surface machined in the operation illus-

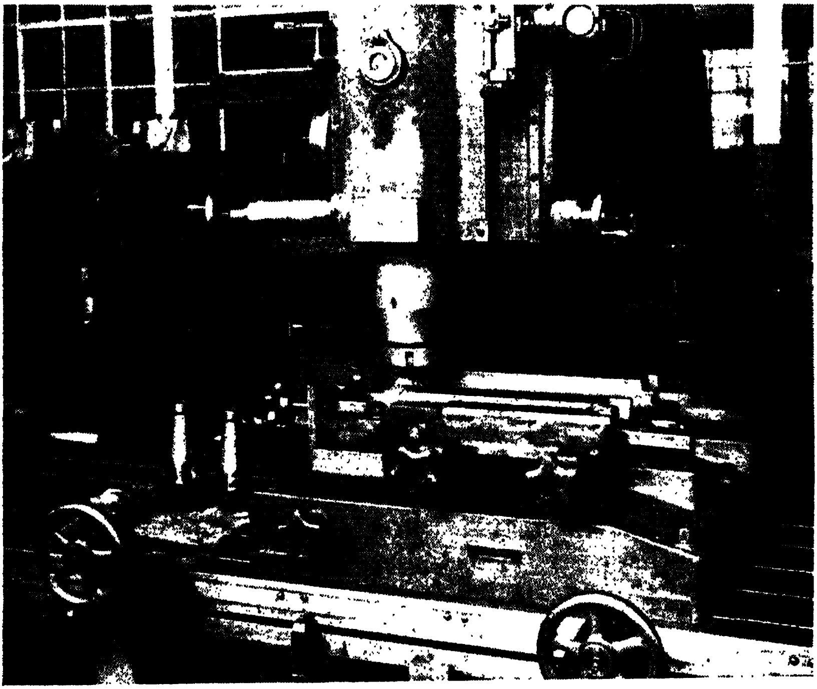


Fig. 214. A machine tool part milled on a vertical milling machine. The surfaces finished include a dovetail and flats. The various cutters needed for the operation are mounted in a quick change adapter.

The fixtures utilize strap clamps bearing on top unfinished surfaces and side and end screws to push the piece against the locators. A jack support, operated by the knob in front, supplements the fixed locators. (Courtesy Cincinnati Milling Machine Co., Cincinnati.)

trated, so that the area available for vertical clamping is limited to strips along the sides.

The condition of clamping surfaces

When the entire top of a piece must be machined, clamping must be confined to the sides. If the sides are rough, the clamps may be made to dig into the surfaces and pull the piece down, like in Fig. 215a. A common example is that of the use of serrated chuck jaws for gripping castings or forgings in initial operations.

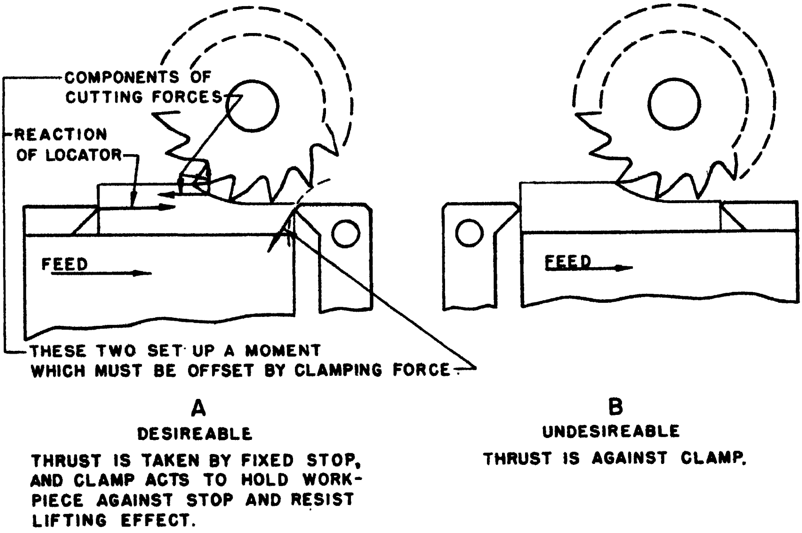

COMPONENTS OF CUTTING FORCES
REACTION OF LOCATOR
FEED
THESE TWO SET UP A MOMENT WHICH MUST BE OFFSET BY CLAMPING FORCE
FEED
A
DESIREABLE
THRUST IS TAKEN BY FIXED STOP, AND CLAMP ACTS TO HOLD WORK-PIECE AGAINST STOP AND RESIST LIFTING EFFECT.
B
UNDESIREABLE
THRUST IS AGAINST CLAMP.

Fig. 215. Forces should be opposed by fixed stops.

If the sides of a piece are finished, friction from the pressure between the clamps and locators must be relied upon to retain the work. The die castings of Fig. 32 have a light cut taken over most of their top surfaces. Each is held against any tendency to pull out by the clamping action of two V's bearing on the side. Even more significant is the case shown in Fig. 216. Each piece held in that fixture is milled on two ends as well as on the top at the same time, and the only available surfaces for clamping are the two sides.

The casting of Fig. 148 is machined on two sides at the same time. Clamping must be confined to the top, necessitating the rigging shown to carry the clamps.

The cutting forces to be opposed

Analysis of cutting forces. In addition to bringing a workpiece into proper location, a purpose of clamping is to hold the piece securely in that position against the action of cutting forces tending to disturb the setting. Thus, in the placement of clamps and locators, consideration must be given to the forces it is necessary to overcome.

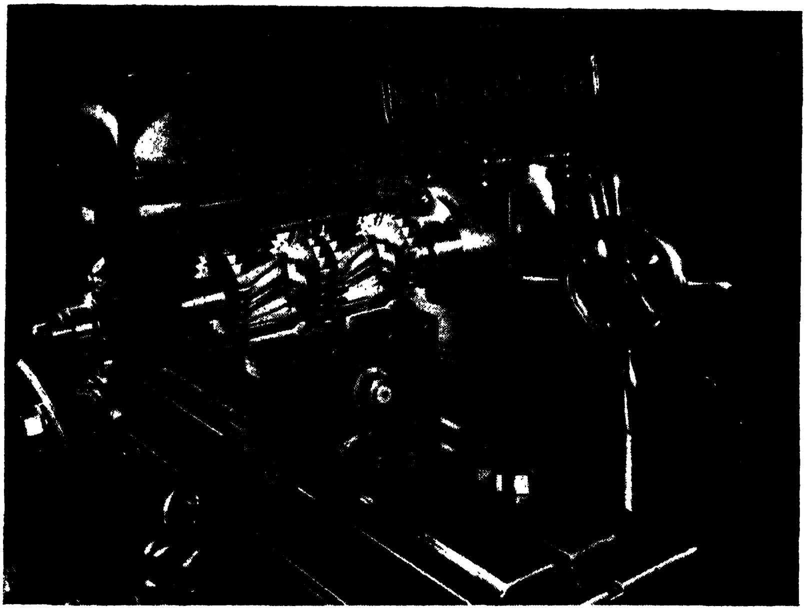
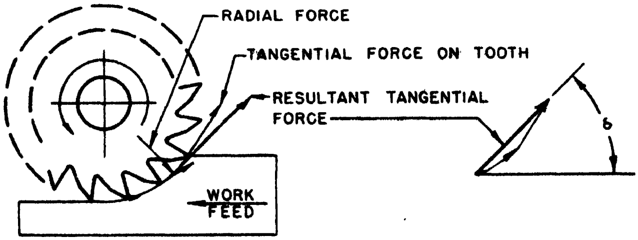


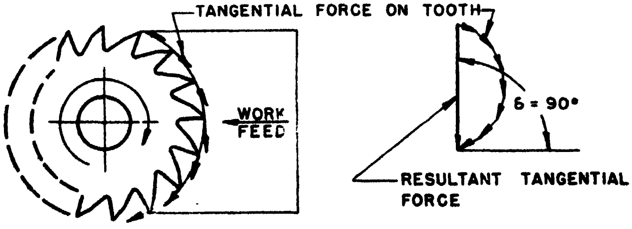
Fig. 216. Two pieces each milled on top and two ends by gang-milling cutters. The parts are gripped in a vise-like fixture, which has the bolt attached to the clamping jaw brought through the body so that the nut is accessible on the operator's side, away from the cutters. (Courtesy Cincinnati Milling Machine Co., Cincinnati.)

A single-point tool turning a piece in a lathe is found to be subjected to a force that has three components. The principal component is the vertical or tangential force, so-called because it is vertical to the top of the tool and tangential to the work surface. There is also a longitudinal or traversing force, arising from the feed or traverse of the tool in the longitudinal direction of the workpiece. A third component is the radial or surfacing force, which tends to separate the tool radially from the surface of the workpiece.

The cutting edges of all tools, single point or multiple point, have been shown to give rise to two or three forces equivalent to those acting on a turning tool. For instance, a straight-tooth plain milling cutter is subject at each cutting edge to a tangential force vertical to the face of the tooth, and a radial force.



A COMPOSITION OF THE TANGENTIAL FORCE IN SLAB MILLING



B COMPOSITION OF THE TANGENTIAL FORCE IN FACE MILLING.

Fig. 217. Forces acting on milling cutters.

The direction of the resultant tangential force upon a plain milling cutter is determined by the individual tooth components. When the cut is shallow, the resultant tangential force may be nearly parallel to the direction of feed, but deviates from the horizontal by an angle δ of Fig. 217A. The angle δ increases as the ratio of depth of cut to cutter diameter increases. In the same way the individual radial components are resolved into a radial force perpendicular to the tangential force.

For a wide cut in face milling where a large number of teeth are engaged in the cut, the resultant tangential component is nearly at right angles to the direction of feed, as indicated by the angle $\delta = 90°$ in Fig. 217B. In addition to the tangential force, radial and axial forces normally may be expected.

The forces in conventional face milling act in horizontal and vertical directions, and the cutting forces described for slab milling may be resolved into two components, one in the direction of the feed and the other normal thereto. For up-milling, the downward component of the radial force may actually exceed the upward component of the tangential force if the cut is shallow, and the vertical component acts downward.[1] As the depth of cut is increased the vertical component actually reverses in direction and must be opposed by a vertical clamping force. In down-milling, the vertical force is always downward and increases in intensity with the depth of cut.

Similar analyses can be made to determine the directions of the cutting forces and their components with respect to the locators in any kind of machining operation. However, it should be emphasized that such analyses can only be looked upon as estimates.

In addition to the actual cutting forces, moments that may be produced and must be resisted should not be overlooked. In slab milling, for instance, the horizontal component should be placed as near to the elevation of the side stops as possible, but often must be somewhat above. Thus, a moment is created between the horizontal component and the reaction of the locator, as indicated in Fig. 215.

The directions of cutting forces and their components are comparatively easy to ascertain, but an estimate of their intensities is often difficult to make. In the first place, the forces depend upon the conditions under which the operation is conducted; the feed, speed, depth of cut, etc. It is not always possible to predict just what these will actually turn out to be. Although investigations have been made of the forces encountered with many materials, tools, and under many cutting conditions, it may not be possible to find data applicable exactly to every specific case. However, it is quite feasible on most occasions by the exercise of judgment to estimate the extent of the largest forces that may act. If there is any doubt as to their sufficiency, a factor of safety may be appropriate to cover contingencies. It is the extreme condition that clamping must be prepared to meet.

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[1] *A Treatise on Milling and Milling Machines*, Vol. 2, pages 298–303. Cincinnati, Ohio: The Cincinnati Milling Machine Company, 1946.

Within the space of this text, no comprehensive presentation can be made of the subject of metal cutting. For basic information about cutting forces, reference is made to handbooks, manuals, and treatises on the subject, specifically to those cited in the bibliography at the end of this chapter. To illustrate the analytical use of such data, some examples follow.

Example 25: The workpiece in the jig of Fig. 218 is cast iron. Two holes, each 3/8-in. diameter, are to be drilled through the end bosses. The drill is to be fed at 0.007 in. per revolution. What is the thrust force acting at each hole?

According to Boston,[2] the thrust B for cast iron in terms of feed f and drill diameter is:

$$
\begin{aligned}
B &= 14{,}720 f^{0.6} d \\
&= 14{,}720 \times 0.007^{0.6} \times \tfrac{3}{8} \\
&= 281.2 \text{ lb}
\end{aligned}
$$

Differences in web thickness, dull drills, and variations in material may bring about a greater than the theoretical thrust. Excessive forces are not

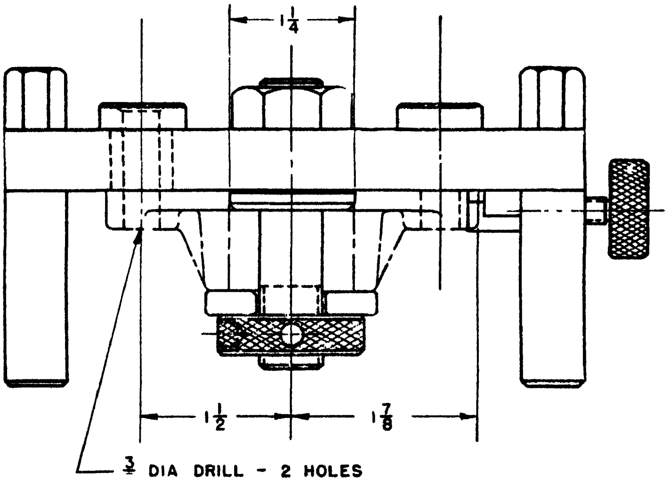

Fig. 218. A sketch of a drill jig.

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[2] O. W. Boston, *Metal Processing*, page 271. New York: John Wiley and Sons, Inc., 1941.

normally as dangerous in drilling as in milling. The part is fully enclosed, so there is little chance for it to escape. Any movement of the piece can only be in the direction of the hole, and only small location errors are likely to be introduced by even very large overloads. Consequently, a factor for contingencies of 1¼ should be ample for most drilling operations, and many satisfactory drill jigs have allowance for none at all.

With a factor of 1¼, the maximum estimated thrust per hole is:

$$281 \times 1.25 = 350 \text{ lb (approx.)}$$

Example 26: The piece of Fig. 219 is 1 in. in diameter and 6 in. long. A groove 3/16 in. wide and ¼ in. deep is to be milled in it. The cutter is H.S.S., 6 in. in diameter, runs at 100 s.f.p.m. or 64 r.p.m. (approximately), has 16 teeth, and is to be fed at 0.006 in. per tooth.

The feed rate is

$$0.006 \times 15 \times 64 = 5.76 \text{ in./min}$$

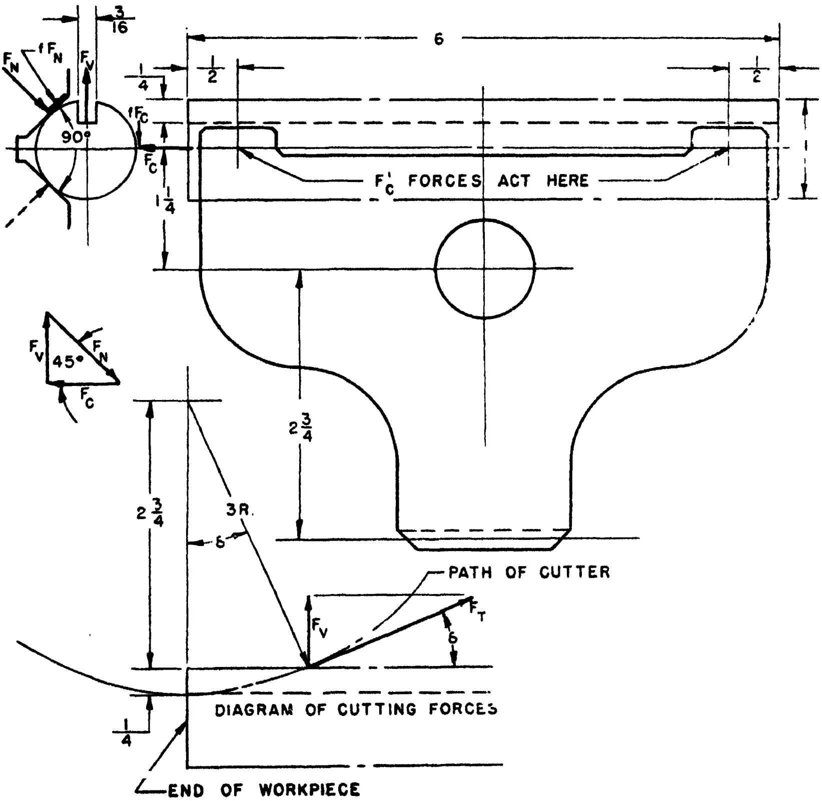

Fig. 219. The forces acting on a round piece held in a V.

The metal removal rate is

$$\tfrac{3}{16} \times \tfrac{1}{4} \times 5.76 = 0.270 \text{ in.}^3/\text{min}$$

The power required[3] is

$$2.5 \times .27^{3/4} = .934 \text{ h.p.}$$

The tangential force[3] is

$$F_T = \frac{.934 \times 33{,}000}{90} = 342 \text{ lb}$$

The position of F_T, for which its vertical component, F_V, is a maximum, is tangent to the cutter at the top of the work. As indicated in Fig. 219, F_T then acts at an angle δ, such that,

$$\cos\delta = \frac{2.75}{3} = 0.9167$$

or

$$\delta = 23^\circ\, 33'$$

and

$$F_V = F_T \sin\delta = 342 \times 0.3996 = 137 \text{ lb}$$

In addition, there is a radial force with a downward component, which would act to reduce the total vertical force. If that is neglected, the estimate is that much more conservative. An arbitrary factor for contingencies of 2¼ gives:

$$137 \times 2\tfrac{1}{4} = 308 \text{ lb maximum vertical force}$$

which may be taken as the extreme value for F_V.

Problem 75. The cylinder block of Fig. 142 is rough bored to 2.480-in. diameter by a four-blade boring tool that removes ⅛ ± 1/16 in. of stock from a side at a feed of 1/64 in. per revolution. Of two diametrically opposite teeth, one may be taking a cut 1/16 in. wide and the other 3/16 in. wide at any instant, thus unbalancing the forces between them. The material is cast iron. Estimate the maximum difference between the tangential forces and longitudinal forces acting on the cylinder wall.

Problem 76. A groove ½ in. deep by ¾ in. wide is milled in the piece of Fig. 221 by a H.S.S. cutter, 6 in. in diameter having 16 teeth. The material is S.A.E. 4150 steel with a B.H.N. of 190. Estimate the maximum value of the vertical force F_V.

Problem 77. The piece held in the fixture of Fig. 216 has dimensions and is milled on surfaces indicated in Fig. 220. The material is S.A.E. 3145 steel. A maximum of 1/16 in. stock is removed from each surface. For the H.S.S. cutters shown, estimate the maximum vertical force and horizontal force.

Clamping reactions to cutting forces. A clamp may serve to counteract cutting forces by:

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[3] *A Treatise on Milling and Milling Machines*, Vol. 2, pp. 273 to 299. Cincinnati, Ohio: The Cincinnati Milling Machine Co., 1946.

1. Holding a workpiece against fixed locators to enable them to receive the major thrust, leaving minor forces for the clamp to resist.
2. Taking the thrust directly.
3. Pressing a workpiece against a surface to set up a frictional force.
4. Digging into a workpiece and pinching a workpiece against a sharp locator.

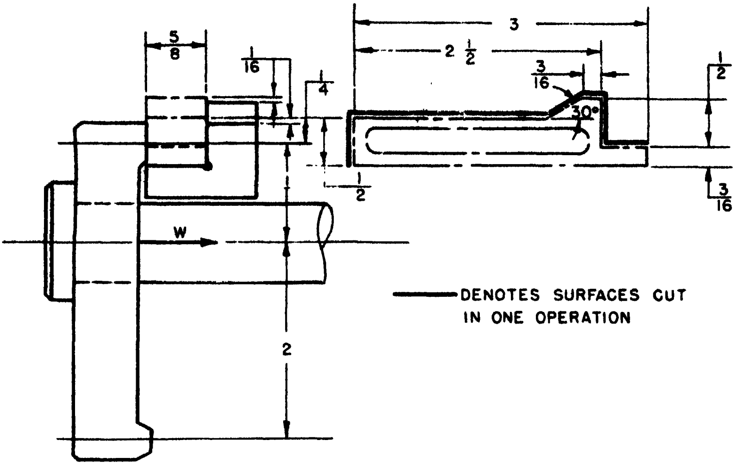

Fig. 220. Workpiece dimensions.

Whenever possible, the principal cutting force or forces should be directed against fixed locating points. This in itself tends to seat the work even more securely in its intended location. Fixed locators are normally more rigid than movable members and more resistant to deflection. Thus, in Fig. 215, the condition shown on the left, where the largest component of the milling force is directed against the fixed stop, is preferable to that on the right, where the clamp takes the thrust.

Provision for adequate clamping requires that the directions of the forces of an operation be determined and that at least a rough estimate of their sizes be made. Then clamps of sufficient strength must be provided to meet forces not otherwise opposed. Pieces located from points arranged in co-ordinate plane on the 3–2–1 principle usually require the most clamping attention. The direction of clamping forces against all locating points is not always possible, as has been shown, so the arrangements take many forms.

In Fig. 214 the ideal is almost achieved in clamping a heavy piece firmly against the locators in three co-ordinate planes. Two screws on the side and one on the end push against the 2–1 locating points, while the strap clamps press down on the base plane.

Each part of Fig. 216 can be clamped in only one direction because of the extensive cut taken over three sides. The fixed jaw of the fixture against which each piece is pressed may be considered the base plane. Thus, in this case, forces in the 2–1 directions are counteracted largely by friction forces.

The casting of Fig. 210 has its entire upper surface milled, which does not allow clamps on top. The nature of the cut is such that the only vertical force is the one caused by the moment between the horizontal cutting forces and the locator reactions. This is taken care of by the squeeze between the horizontal clamps and their opposed locators, which also receive the horizontal forces.

Some types of locators do away with the necessity of clamping in certain directions. A pin or plug eliminates all horizontal movement if used as a locator in a vertical hole in a workpiece. Two such pins eliminate all chance of extensive rotation as well. Consequently, when two pins are used, clamping in one direction only is necessary. This is illustrated by the jig of Fig. 198. The master rod is located on the plug and pin and needs only to be clamped down by the bushing plate.

The light die casting of Fig. 27 locates over pins that confine it horizontally. Vertical forces are incidental and the light toggle clamp is sufficient for holding down the parts.

Sizes of clamping forces. In Fig. 221 the piece is held down by two strap clamps, while a groove is milled through the center. For simplicity we may assume that all horizontal cutting forces are fully opposed by stops, not shown. The vertical component, F_v, is the only one to be neutralized by the clamps. The question is how much vertical clamping force is necessary to prevent the vertical force, F_V, from moving the piece from the base on which it is pressed? If the piece is lifted ever so slightly, location will be impaired. Cutting forces are periodic, and even a momentary rise in the workpiece may result in chatter. These situations must be avoided.

As pointed out before, a fundamental precept of clamping is that a clamping force should be applied directly over a locating surface, if at all possible, through a heavy section of the workpiece that will not spring. In that situation the piece under the clamps is relatively inelastic in comparison with the flexibility of the clamping mechanism.

If the nut on the left clamp is tightened enough to induce a load W on the clamp, a force F_1 is brought to bear on the work, such that:

$$F_1 = W\frac{l - p}{l} \tag{83}$$

F_1 from the clamp is opposed by an equal and opposite reaction (R_1) of the work and is transmitted through the workpiece section to act fully on the locator as F_1'. If the workpiece moves upward, the clamp must likewise move. But the clamp is sprung by the initial reaction R_1; and if the clamp is to be deflected more, R_1 must be increased. Furthermore, since the workpiece section is rigid, the forces F_1' and F_2' will disappear the instant contact between the workpiece and base is broken. Thus, any additions to the reactions, to deflect the clamps more must come entirely from the disturbing force, F_V. As long as the force imposed by a clamp exceeds the reaction at the point of contact caused by the vertical force F_V, no movement of the workpiece can take place. When F_V is less than that contained by F_1 and F_2, it acts merely to reduce the bearing forces F_1' and F_2'.

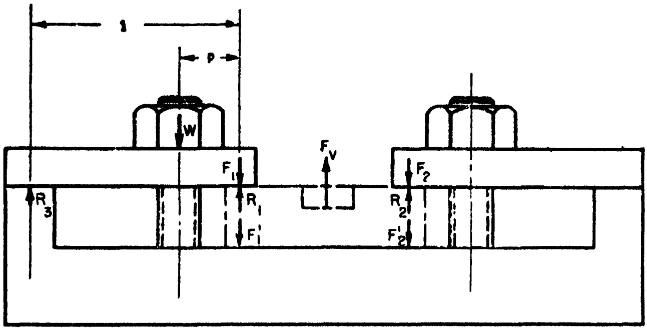

Fig. 221. A workpiece held by strap clamps.

This is an illustration of the principle that a clamp must impress on a workpiece an initial force greater than any reaction it may receive if movement of the workpiece is to be avoided during an operation. The extent to which pains may be taken to eliminate all possible movement is another matter. Usually it is desirable to do so, but for practical reasons some displacement may be tolerated under adverse conditions.

EXAMPLE 27: A thrust of 350 lb per hole was indicated by Example 25 for the piece sketched in Fig. 218. If both holes were drilled at once the load on the clamp washer and nut would be 2 × 350 = 700 lb.

For one hole,

$$W = 350 \times \frac{3.375}{1.875} = 630 \text{ lb}$$

For one or two holes at a time, there is not much difference in the load on the clamp.

EXAMPLE 28: The workpiece illustrated in Fig. 219 and described in Example 26 is held in a V-fixture, similar to that shown in Fig. 222. The maximum vertical cutting force has been estimated to be about 300 lb. What must be the clamping force, F_c, to hold the workpiece in the V against the vertical cutting force, F_V?

When F_c is just great enough to oppose F_V, the reaction from the lower part of the V, indicated by dashed lines in Fig. 219, will have ceased to exist. If friction is neglected, the piece is found to be held by the equilibrium of forces F_V, F_N, and F_C, all passing through its center. They form the force triangle, drawn in Fig. 219, on which $F_c = F_V$ in one plane.

The friction forces fF_N and fF_c are not included, but should be recognized. It is difficult to assign exact values to them, and only small values exist under all conditions. Their exclusion raises the margin of safety and does not add excessively to the requirements.

The clamp bears on the workpiece at two points, with forces F_c', which are assumed equal. If F_V is placed at the end of the workpiece, let $F_c' = 300$ lb and the total load on the end of the clamp = 600 pounds. At the stud,

$$W_{\min} = \frac{4.00}{2.75} \times 600 = 875 \text{ lb (approx.)}$$

Problem 78. The clamping distances for the cylinder block of Fig. 142 are shown in Fig. 223. The clamps are applied on the top surface of the block, 12 in. above the bottom of the base. Using the values for the maximum tangential and longitudinal cutting forces ascertained in Problem 75, calculate the load required at the clamping stud. The part is located on two pins, which resist all torque.

Problem 79. If in Fig. 221, $l = 4$ and $p = 1\frac{1}{2}$, what is the load W? Estimate the cutting forces on the basis of the data given in Problem 76.

Problem 80. For the two pieces described in Problem 77, what is the force W (shown in Fig. 220) that the clamp drawbar must exert if the coeffi-

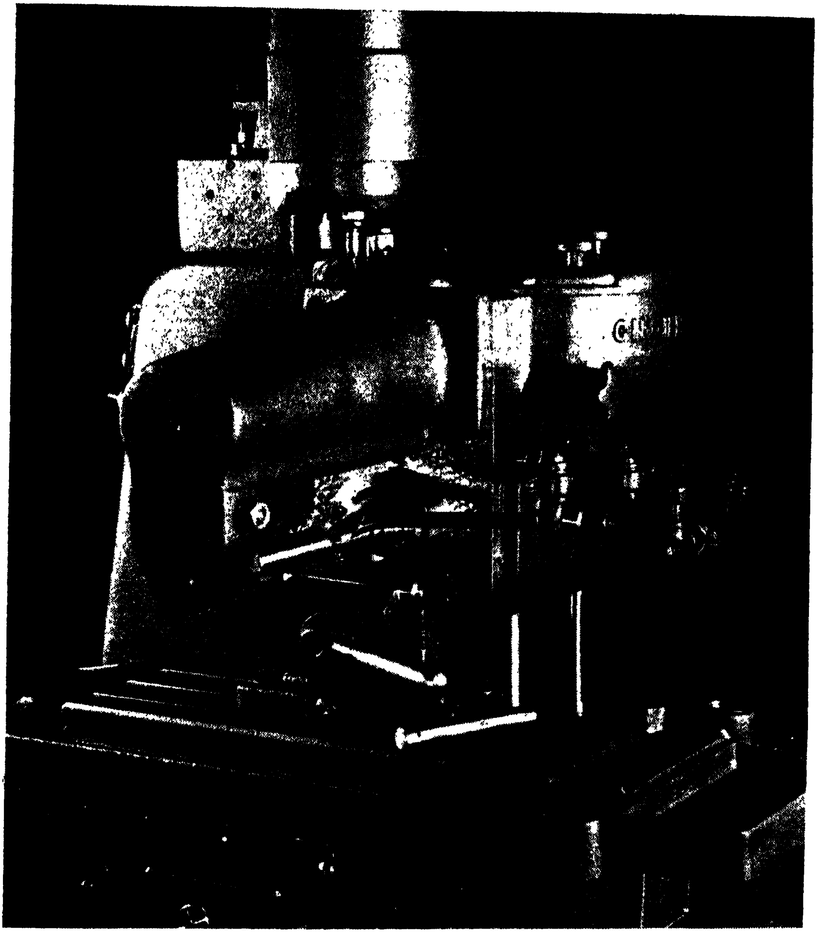

Fig. 222. A fixture for milling a groove or flat on a round bar. The workpiece is located in a V and against an end stop. A single clamp grips the piece. The clamping handle does away with the necessity of using a loose wrench for clamping and unclamping. (Courtesy Cincinnati Milling Machine Co., Cincinnati.)

cient of friction between clamp or locator and workpiece is taken at 0.3? If $f = 0.10$?

THE ECONOMY OF CLAMPING

There are only a few basic types of clamps, but many variations of each. Large numbers of these are nicely illustrated in texts and reference books of descriptive tool design, and it is not within the scope of this text to duplicate those presentations. To suit the requirements of any particular application, one or more variations of several types are usually available. The choice of one from those rests upon economics. The economic principles governing choice with specific references to clamping devices were covered in Chaps. 3 and 4.

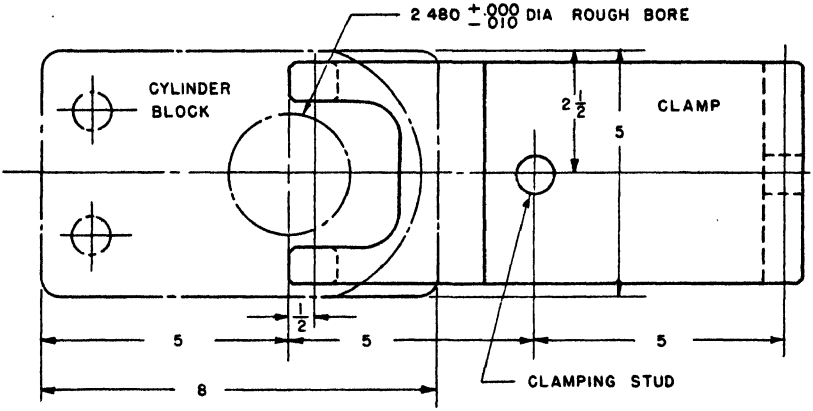

Fig. 223. Clamping distances for cylinder blocks.

Combined clamps

For heavy pieces and severe operations, separate clamps may have to be installed for each direction of location, sometimes several clamps in one or two directions. That has been done for the cases of Figs. 214 and 231. For light pieces and cuts it is often possible to arrange for one clamp to serve for more than one direction of location. Obviously, economy is promoted by reducing the number of clamps requiring attention in an operation.

The components of a single clamping force. The simplest form of combined clamp is one placed with its line of action between two desired clamping directions so that its components act against two sets of locators. Such an arrangement is indicated by Fig. 224, where the clamping force F_H is directed so as to bring components to bear on the locators A, B, and C. One problem is to determine the direction and position of the single force to set up equal reactions at all the locating points. In other words, in Fig. 224, what shall be the position and direction of F_H, so that $R_1 = R_2 = R_3 = R$?

The resultant of R_2 and R_3, equal to $2R$, passes through D, midway between R_2 and R_3 extended. Since three coplanar forces in equilibrium must be concurrent, F_H also passes through D, which is the same distance, a, from the side of the piece as R_1. If friction is neglected,

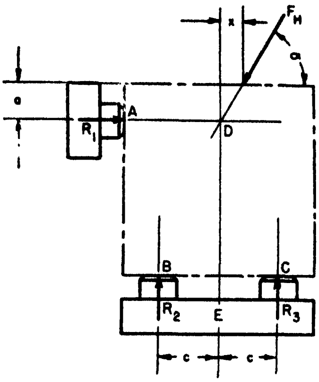

Fig. 224. A single clamping force opposed by three locators.

$$\tan\alpha = \frac{2R}{R} = 2$$

and

$$\alpha = 63^\circ\, 26'$$

also

$$\frac{a}{x} = \tan\alpha \qquad \text{and} \qquad x = \frac{a}{2}$$

Thus, the point of application of F_M depends only on a for the conditions specified.

Problem 81. Let X be any distance from ED, along the side of the piece. F_H is applied at an angle δ to pass through D. What is the relationship between R_1, R_2, and R_3?

Problem 82. Let F_H be applied at any point along the side of the piece at a distance X from ED at such an angle V that it does not pass through D. What is the general relationship between R_1, R_2, and R_3?

The combined clamping action of centralizers. Only a single clamping force through one section is normally applied to hold a piece in a V, like in Fig. 212E. The force is evidently most effective when it passes through the center of the V in that the reactions from the sides then are equal.

Although clamping is a secondary function of centralizers, such devices do have the advantage of being able to deliver forces in two directions from a single application. In Fig. 170, the centralizing V, which acts as a clamp, and the fixed V are modified by having a slight taper in their inside faces. That makes it possible to fix the piece in all three directions by means of one clamping movement.

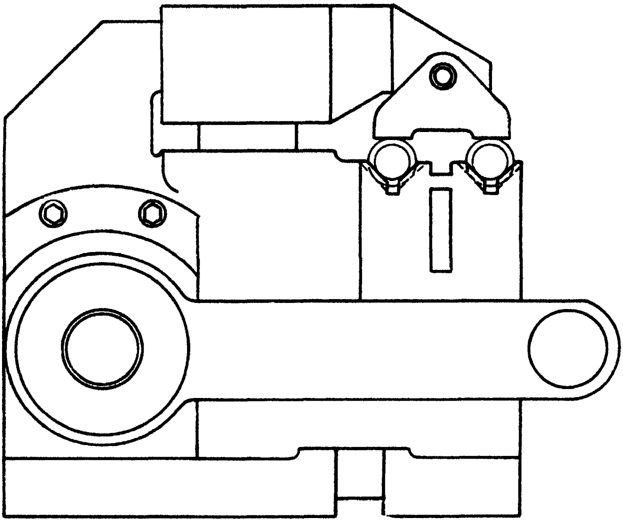

Fig. 225. A universal fixture adapted for holding two pieces for straddle milling their ends. The cylindrical pieces are located in V blocks and clamped through an equalizer by one movement of the clamping lever. (Courtesy Swartz Tool Products Co., Detroit.)

For the light milling operation of Fig. 32, the pieces are adequately held between two V's, and each is clamped by the movement of one lever.

Equalizers. Clamping devices that serve to distribute one clamping effort over two or more surfaces are known as equalizers. As the name implies, such a device tends to equalize the clamping force between the surfaces to which it is applied. The surfaces may be on one part or they may be on different parts. In other words, equalizers make it possible to apply forces to one part in more than one spot by a single action, or to clamp several parts by one motion. Obviously, this means a saving of clamping effort in any case where it is used.

Equalizers are not to be confused with centralizers. The primary object of the latter is to provide specialized location. That they also give a certain amount of clamping is secondary, although beneficial. The sole purpose of equalizers is to clamp. Accordingly, centralizers are usually mounted in a specific and related manner with respect to the other locators, usually on the body of a jig or fixture. Like other clamps, equalizers may have a somewhat variable position with respect to the locators, on comparatively free members like a swinging arm of a fixture or the leaf of a jig.

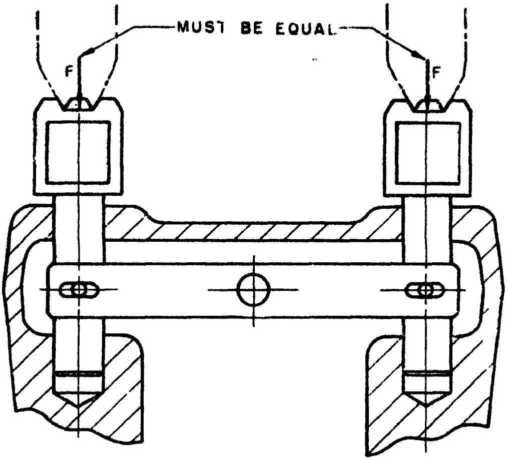

Fig. 226. A diagram of an equalizing device.

The commonest form of equalizer is a pivoted clamping bar. Such a device is incorporated into the fixture of Fig. 225. The contact pad for two pieces is pivoted on a pin through the clamping arm. Both workpieces are held in place by the movement of the one clamping bar.

The bottom conical locators for the two pieces held in the jig of Fig. 43 are mounted on an equalizer, in the manner sketched in Fig. 226. When the bushing plate descends to clamp two parts at once, the equalizer compensates for unequal lengths and supports the pieces evenly.

Equalization is accomplished through springs in the jig of Fig. 44. When the two heads are brought down on pieces of unequal thickness by the action of the single lever, contact is assured for both by the pressure supplied by the springs on the vertical shafts shown at the rear. Normally, these springs are covered, but the covers have been removed to reveal the presence of the springs.

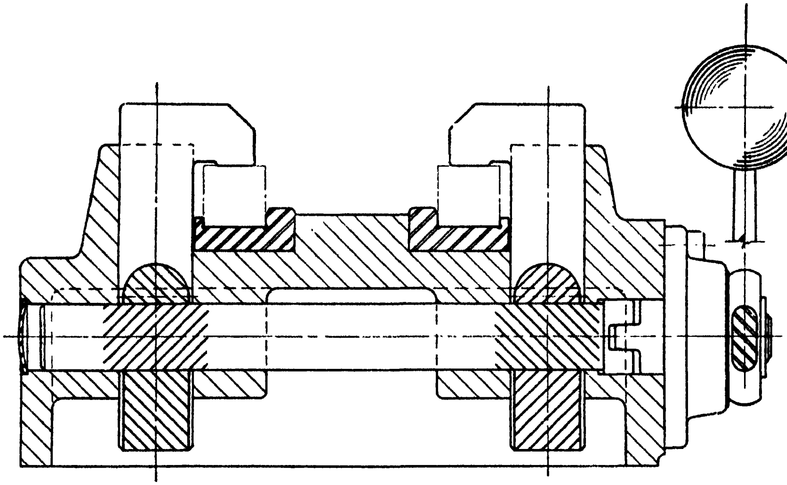

Fig. 227. A cross section of a standard universal fixture arranged for double-equalized clamping. Through the single lever, the cross shaft with spiral teeth is turned. Its teeth contact spiral teeth on the vertical clamping posts. The cross shaft is allowed a certain amount of end play. When one of the clamps is seated and stops moving, the cross shaft can continue to turn, moving axially, until it brings the other clamp in contact with its piece. (Courtesy Swartz Tool Products Co., Detroit.)

Another type of equalizer utilizes the principle of spiral gearing, as sketched in Fig. 227. Two clamps are brought down on two unequal surfaces by a single lever acting through a cross shaft. The clamp posts have spiral rack teeth that engage with spiral teeth on the shaft. When one clamp is brought to bear before the other, the cross shaft continues to turn, by moving axially, and draws down the second clamp until it is tight.

In Fig. 228 a milling fixture for a manifold is shown that equalizes the clamping pressure supplied by the one upper lever onto four flanges. The effort is first divided into two parts by a spiral gear mechanism already described; and then each component is again divided by a pivoted bar equalizer.

Ordinary clamps may have a certain amount of equalizing effect.

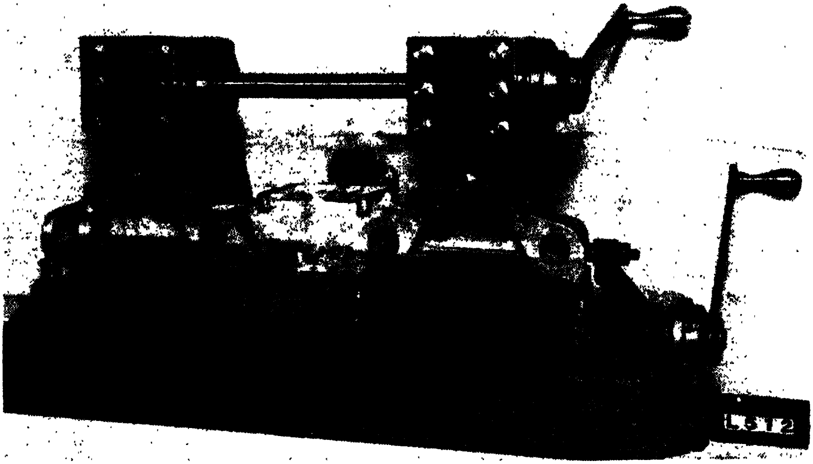

Fig. 228. A rapid and convenient milling fixture for a manifold. All four flanges are clamped by the equalizing mechanism at the top. This mechanism makes use of both the spiral gear equalizer and pivoted bars, in order to divide the clamping effort four ways. In the base, 4 adjustable supports are actuated by one lever. (Courtesy Swartz Tool Products Co., Detroit.)

A clamping plate or strap, like any other object, must have at least three points of bearing, and more are superfluous. The typical strap clamp, sketched in Fig. 229, illustrates how the bearing points may be emphasized in the shape of the clamp. The curvature on the

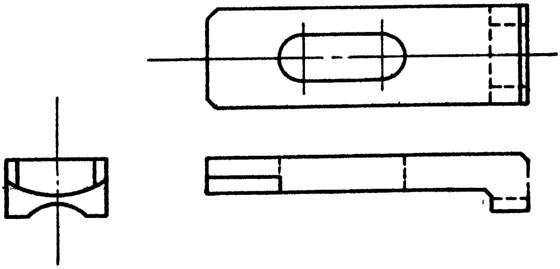

Fig. 229. A typical strap clamp having three-point bearing.

bottom of one end of the body approaches a single contact point. The other end is relieved except for two points. Either end may be made to bear on the workpiece surface, depending upon whether one or two points of contact are desired there. Such a clamp can be arranged to accommodate reasonable irregularities in the workpiece.

Figure 142 shows how advantage may be taken of a three-point bearing. The clamp over the top of each piece is forked to provide

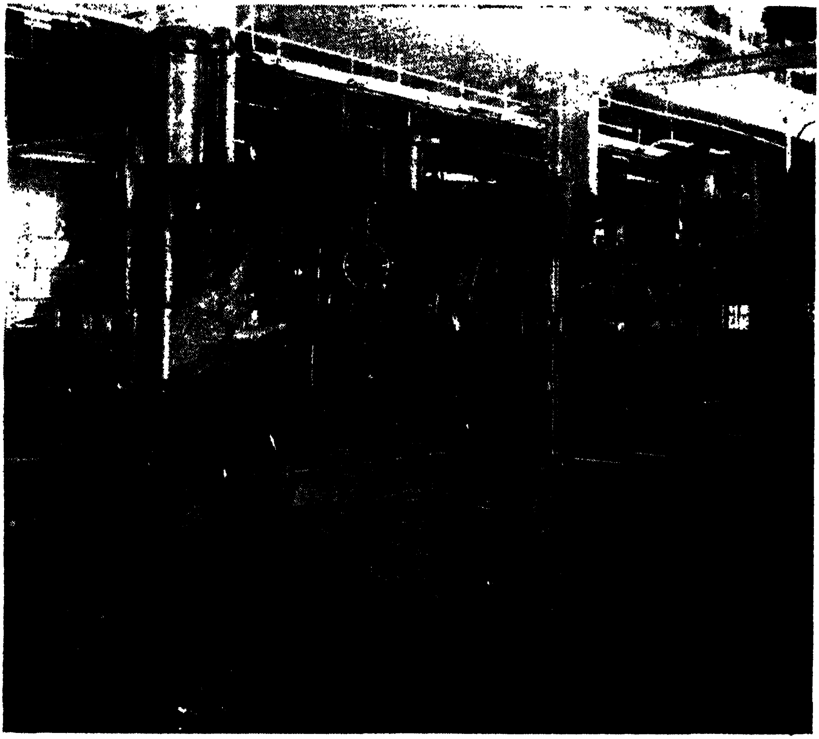

Fig. 230. A hole-spacing device being used in conjunction with a standard radial drill for positioning and drilling holes in a workpiece. This arrangement is commonly used to supplant jigs in manufacturing. The work is located in a definite position on the table of the positioner. The table is carried upon a saddle. Movement is obtained hydraulically in two co-ordinate horizontal directions and positioning is accomplished automatically through a series of accurately preset stops on both table and saddle. Repetition of settings is secured to very small tolerances. The radial arm of the drill press is supported by an outboard support to add rigidity. (Courtesy Bullard Co., Bridgeport, Conn.)

clearance for the boring tool, but also to hold down the cylinder on two sides of the bore. In Fig. 141 the strap clamp is forked to divide the pressure between both sides of the flange, adding to the stability of the setting.

The round piece of Fig. 222 is sufficiently long to benefit from the equivalent of four points of contact from the V and is held against these four points by the one clamp. In addition, friction is enough to prevent turning about the workpiece axis and keep the piece from moving away from the end stop.

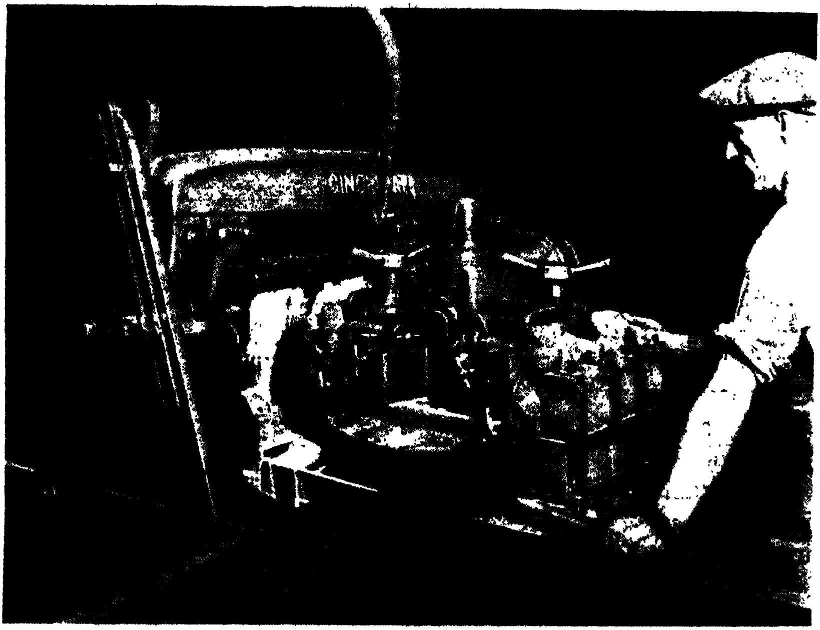

Fig. 231. A milling operation for removing flash and cutting necessary clearance at bottom between the bosses of a steering knuckle. The installation provides means for reducing the cycle time of the operation in two ways. A variable hydraulic-feed manufacturing-type milling machine is used that permits a high feed rate across the bosses, where the cut is very light, and a slower feed when the cutters bottom between the bosses. Also, the fixture is mounted on an automatic indexing base which rotates 180° when the movement of the table withdraws it from the cutters. The operator has only to load and unload the workpieces, which he can do two at a time during the cutting period, and start the automatic cycle. A copious supply of coolant washes the chips away from the cutting area down the slots for that purpose into a pan from which they can be removed conveniently in bulk. (Courtesy Cincinnati Milling Machine Co., Cincinnati.)

In Fig. 231 a single clamp is brought to bear on the tops of two pieces at the same time.

There are other types of equalizers; some operated by rollers, balls, heavy confined grease, or conical contacts. No matter what the means, the principle for all is the same as for those described.

THE SOURCES AND SIZES OF CLAMP-ACTUATING FORCES

Manual clamping forces

Most clamps are hand-operated. What they can do depends upon what can be put into them. The force that an operator can exert on a lever or handle depends on his strength. It is well known that human strengths vary widely. What is a light task for one person may be too much of a burden for another. A person cannot expend his utmost continuously for a long period of time. If movements are frequent, the loads must be lighter than if they are widely spaced. To judge how much a clamp must be able to increase the force applied to it, we must have some idea of the *least amount of force* that it is reasonable to expect will be put into it.

The force that a clamp puts out reacts back on it. A sensitive device that gives a large clamping force when manipulated by a weak operator may be subjected to tremendous reactions when operated by a strong person. Thus, a clamp must be arranged to hold tightly with reasonable effort and also be rugged enough to withstand abuse. To judge the stress to which a clamp may be subjected, we must have some idea of the *largest forces* that may be imposed on it.

Manual clamping forces vary with the application. There are many muscle groups in the human body that can be put into action to exert forces. One act may require one group; another act a different group. For any one person, a specific effort has been shown to vary with the height and distance at which it takes place.[4] An operator can pull harder on a lever in a convenient position than if it is too high or too low. He can pull more with one type of lever than another. An approximation of the maximum forces that it was found average individuals could exert on several types of levers is given in Table 8. It should be understood that for any particular device the actual force will be somewhat different, depending upon the position of the lever. However, these discrepancies, except for unfavorable conditions, are much less than the differences between many people.

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[4] See Chap. 4.

TABLE 8

SUMMARY OF MANUAL FORCES EXERTED ON VARIOUS TYPES OF LEVERS

	Average Force (Lbs)
Single lever:	
Push or pull vertically from about 20 to 35 in. above floor level	95
From about 35 to 50 in. above floor level	65
Push or pull horizontally	65
Crossbars:	
Push and pull vertically or horizontally; unfavorable positions eliminated	160
Handwheel:	
Vertical and parallel to body	125
Vertical and perpendicular to body	160
Horizontal	140

These figures are intended to give an approximate idea of forces that can be exerted on controls. The actual force exerted in any case varies considerably with the position of the control and the physique of the operator. The values provide a rough guide for estimating reasonable loads for clamping devices.

The averages are based on studies of W. P. Kühne, "Studies on the Optimum Force Exerted on Machine Controls," *Industrielle Psychotechnik*, Vol. 3, No. 6, pp. 167–172, June 1926, as reported by R. M. Barnes, *Motion and Time Study*, p. 239, John Wiley and Sons, Inc., 1940.

The Siewek Tool Co. has determined that 85 to 100 in.-lb torque can be exerted on hand knobs without the use of a wrench.

The strength of a person can be measured on a dynamometer. However, testing of all the strengths of an individual is not necessary to find his overall physical ability. Cureton has reported[5] that the intercorrelations between various dynamometrical strength tests average about 0.90. Four events, right- and left-hand grips, back lift, and leg lift, are considered proportional to total strength. Table 9 lists the averages of these strengths, as well as a few others, for a large number of cases.

The distribution of human strengths, like many other physical phenomena, may be approximated by a normal curve. Most of

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[5] T. K. Cureton, *Physical Fitness Appraisal and Guidance*, page 368. St. Louis, Mo.: The C. V. Mosby Co., 1947.

TABLE 9

RESULTS OF STRENGTH TESTS

Action	Force in Pounds					Source
	Maximum	Mean	Minimum	Max. / Min.	Min. / Mean	
Grip	166	109	52	3.2	0.48	(1)
Grip	148	95	42	3.5	0.44	(2)
Grip	154	103	52	3.0	0.51	(3)
Right grip	183	124	65	2.8	0.52	(4)
Left grip	165	113	61	2.7	0.54	(4)
Back lift	568	364	160	3.6	0.44	(1)
Back lift	496	314	132	3.8	0.42	(2)
Back lift	545	368	191	2.9	0.52	(3)
Back lift	541	343	145	3.7	0.42	(4)
Leg lift	1012	617	322	3.5	0.52	(4)
Arm push	464	252	40	11.6	0.16	(4)
Arm pull	115	79	33	3.5	0.42	(4)
				4.0	0.45	Average

(1) 10,593 employed males—14–65 years of age.
(2) 1,328 unemployed males—14–65 years of age.
(3) 1,735 students—16–40 years of age.
Reported by E. P. Cathcart, E. R. Hughes and J. G. Chalmers, "The Physique of Man in Industry," Industrial Health Research Board, Medical Research Council, London, England, No. 71, 1935.

(4) Averages for 250 entering college men reported by F. W. Cozens—"Strength Tests as Measures of General Athletic Ability in College Men," *Research Quarterly of American Association for Health and Physical Education*, Vol. XI, No. 1, March 1940.

the cases are clustered around the mean. Away from the mean in both directions the number of cases becomes less and less. In this tabulation the maxima and minima have been taken at the three sigma limits of the reported observations, within which practically all cases fall. The figures indicate that the greatest strength in most actions is normally between three and four times the least. Also, that the lowest is a little less than half the mean.

If a clamp were made to impose a force of 500 lb when 30 lb were applied to it, it is possible that someone might fasten the clamp with a force of 120 lb and cause it to impose a load of 2000 lb, four times the minimum. As a result, the clamping mechanism would suffer a reaction of 2000 lb instead of the normal 500 lb. Consequently, the device must be made to withstand at least 2000 lb, although intended to deliver only 500 lb for satisfactory service.

Actual exertion is not always the utmost. General figures, like those given, can at best serve only as a guide to judgment in assigning values to the strength that may be applied to any specific control. This was brought out a number of years ago in the experience of a machine tool manufacturer. A semi-special production milling machine was developed for the automotive industry, and a large number of the machines were put into service successfully in Detroit. The starting lever on that type of machine was connected directly to a large hydraulic valve and required a force of about 90 lb to turn it over at the beginning of each milling cycle. Unskilled, but strong, operators ran the machines, and no complaint was heard about any difficulty. Later, several of the same kind of machines were sold to a gun manufacturer in New England. The work to which they were put was not so repetitive and required a higher degree of skill. The workers in the gun plant objected to the effort required to start the machines. For the degree of skill required, it was difficult to find men willing to put forth the continual effort needed to run the machines. The millers eventually had to be altered so that they could be started through a pilot valve, requiring much less effort.

In many cases the willingness of an operator may have more bearing upon the effort he puts forth than does his ability. Generally, people are inclined to exert less than their utmost. The frequency of an action has a decided influence upon willingness. A person is more able and agreeable to make large exertions if they are spaced at intervals than if they must be continuous. In each case judgment must be exercised in estimating a probable lower level of performance. The clamping device must then be proportioned to act adequately with that least expected input. In all cases, that level should be well below the range of strength of the class of operators handling the device.

Air and hydraulic sources of clamping forces

To supplant manual effort, air or hydraulic cylinders are often used to actuate clamping devices. Sometimes force is applied directly from a piston rod for clamping, but it is considered better practice to transmit the force through a linkage that is self-locking and steps up the force. If the air or hydraulic pressure should fall off at a critical time, the self-locking feature keeps the clamped object from coming loose. The use of mechanical advantage allows a lower pressure for the same size of cylinder than would be needed if there were no advantage.

Clamping pressure should be applied to the rod side of a piston, and the releasing pressure to the full area. The force for release will thus be greater than that for clamping, and there will be less likelihood of sticking clamps. The force provided by the pressure on the rod side of the piston must, of course, be adequate to meet clamping requirements.

For an air or hydraulic cylinder, the clamping force, in pounds, delivered is

$$\begin{aligned} F_c &= A_R P \\ &= (A_F - A_L)P \\ &= \frac{\pi}{4}(D^2 - d^2)P = 0.7854(D^2 - d^2)P \qquad (84) \end{aligned}$$

where

A_R = area on the rod side of the piston, in square inches,
A_F = full area of piston, in square inches,
A_L = cross-sectional area of rod, in square inches.
D = diameter of piston, in inches
d = diameter of rod, in inches
P = air or hydraulic pressure, pounds per square inch.

Most factories have air under 80 to 100 lb/in.^{2} pressure,[6] but in many cases it may drop as low as 40 to 50 lb in remote areas, especially if the compressors are overburdened.

Hydraulic pressure is usually secured from individual units, although sometimes it may be taken from the machine circuit, if the machine has a hydraulic drive. Commercial units are available to supply almost any pressure up to 1000–1200 lb/in.^{2}, and even much higher if desired.

The economic advantages of air and hydraulic clamping were discussed in Chap. 4.

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[6] Harry L. Stewart, "Air and Hydraulic Clamping for Jigs and Fixtures," *The Tool Engineer*, Dec. 1948, Vol. XXI, No. 6, page 25.

PROPORTIONS OF CLAMPING DEVICES

Types of clamps

A clamp must impose a minimum force in a definite direction and maintain that force as long as needed. But in any specific case, a clamp is also subject to restrictions of space, accessibility, and maneuverability. To meet these requirements is a problem calling for a knowledge of proven devices, ingenuity, and analysis.

All fasteners employ one or more variations of the simple means of securing mechanical advantage. These are the wedge and its more intricate aspects, the screw and cam, and the lever, including its composite form, the toggle. The lever is commonly used together with at least one of the others because of its simplicity.

An acquaintance with an array of proven constructions is helpful in choosing the right type of clamp for a particular situation. Many forms are shown in books of descriptive tool design. In addition, ingenuity is often needed to arrange a clamping device to fit a set of circumstances.

Analysis of clamps

A clamp must have enough leverage to deliver the load required of it when actuated by available force. Most clamps must also be self-locking; stay in position when the applied force is removed. All forms but the simple lever can be made self-locking or nonreversible; but that property may vary with each, depending upon the given proportions.

A clamp must have sufficient strength to resist deflection and even destruction from the forces and reactions acting upon it and between its own members. Most clamp details may be proportioned for strength on the same basis as other machine and tool elements. In many cases, ample bulk suffices, but sometimes too much interferes with the action of the clamp. For instance, a shaft on which a cam turns must be large enough to stand up, but the larger its diameter, the more the torque of friction subtracts from that available for clamping.

The principles that prescribe the proportions of clamps for leverage, stability, and strength are well known. They are found in texts on mechanics, resistance of materials, and the design of machine elements. Space does not permit a review of those subjects in this book.

EXAMPLE 29: The fixture sketched in Fig. 219 and described in Examples 26 and 28 must transmit a minimum force of 875 lb through the bolt carrying the clamping nut.

Assume that the operator is able to apply an average force of 65 lb to the wrench for tightening the nut. The force may, at times, be as low as 30 lb, but sometimes as high as 90 lb.

What should be the diameter of the bolt and the length of the wrench?

If the application of 30 lb on the wrench is to induce a force of 875 lb in the bolt, that member must be able to withstand a proportional force of 2625 lb caused by the application of 90 lb to the wrench. A permissible tensile stress of 10,000 lb/in.^{2} over the root area of the bolt may be assumed. Thus:

$$2625 = 10{,}000 \times \frac{\pi d_r^2}{4} = 10{,}000 \times \frac{\pi d^2}{1.44 \times 4} = 5454d^2$$

where

$d = 1.2d_r$ = nominal diameter of bolt, in inches,
d_r = root diameter of bolt, in inches.

$$d = \sqrt{0.48} = 0.694 \text{ in.}$$

Choose a bolt $^{11}\!/_{16}$ in. in diameter.

A practical relation between the torque on a nut and the force induced in a bolt is:[7]

$$T = FL = 0.2dW \tag{85}$$

where

T = torque on nut, in inch-pounds,
F = force at end of wrench, in pounds,
L = length of lever arm, in inches,
d = diameter of bolt, in inches,
W = force induced in bolt, in pounds.

In this case,

$$L = \frac{0.2 \times 0.688 \times 875}{30} = 4 \text{ in.}$$

It may be desirable to add an inch or two to the length of the wrench to suit the operator's grasp.

Problem 83. The necessary load on the stud at the roughing station of Fig. 142 was called for in Problem 78. Find the size of the stud and the length of wrench needed.

Problem 84. For the fixture of Fig. 221, specify the size of stud for each clamp and a suitable wrench length to provide the load W called for in Problem 79.

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[7] M. F. Spotts, *Design of Machine Elements*, page 117. New York: Prentice-Hall, Inc., 1948.

Problem 85. For clamping the two pieces described in Problems 77 and 80, find a suitable size for the thread on the clamp drawbar and the length of wrench needed.

SUMMARY

The first purpose of clamping is to press a workpiece against the locators. This action must conform to the positions of the locators, the surfaces on which contact can be made on the workpiece, and the strength of the part. The second purpose is to maintain location in opposition to cutting forces tending to upset the fixation. Satisfaction of that purpose demands compliance to the force relationships revealed by the study of metal cutting.

Whenever possible, the principal cutting forces should be directed against fixed abutments, but that cannot always be done for all forces and moments. Clamping and frictional forces must be introduced to counteract cutting forces not otherwise restrained. The initial clamping forces induced must be larger than the forces they are intended to oppose to prevent workpiece movement.

The most economical clamping device under a set of circumstances is the one that should be chosen for the assignment. To promote economy, clamping functions may often be combined so that two or more can be performed by one device. That may be done by positioning clamps advantageously or by using equalizing clamps to distribute clamping forces appropriately from a common source.

A clamp transmits and usually amplifies forces applied to it. What it can do depends upon what is put into it. What it must withstand depends upon the treatment it receives. Where clamps are hand-operated, the range and average of human strength determines the forces applied. Judgment must be exercised in estimating what that may be in specific situations, but measurements that have been made of human abilities are helpful as a guide. For air or hydraulic operation, the applied force is the product of the pressure times the area on which it acts.

A determination of the proportions a clamp must have to meet a specific situation in accordance with the principles of clamping is a problem of mechanics.

QUESTIONS

1. What considerations are involved in the choice of a clamp?

2. What factors affect the positions, directions, and sizes of clamping forces?

3. Which must come first, locating or clamping? Why?

4. What effects do locating means have upon the positions and directions of clamping forces?

5. Why must the strength of the workpiece be considered for clamping forces? In general, over what sections of a workpiece should clamping forces be brought to bear?

6. If a clamping force cannot be applied over a fixed locator, how may it be opposed?

7. What forces act on a single-point tool? A multipoint tool? A milling cutter? Can their sizes be estimated?

8. In what ways may a clamp act to counteract cutting forces?

9. Where should the principal cutting forces be directed, whenever possible?

10. Are the direct cutting forces the only ones to be considered? If not, what others may be present?

11. How large a force should a clamp exert on a workpiece? Is it always practical to do so?

12. From what arrangements may combined clamping action be obtained?

13. What are equalizers? How do they differ from centralizers?

14. Do all clamps have equalizing effects? Explain.

15. Why is it desirable to be able to estimate upper and lower human strength limits?

16. Is the average clamping force that can be exerted by hand the same for all kinds of levers? In general, how does it vary?

17. How is human strength measured? How is it distributed?

18. How can strength data be helpful in the solution of clamping problems?

19. What is an average practical figure for the ratio between high and low strength?

20. What is the most desirable practice in applying force from a piston rod for clamping?

21. What are typical air and hydraulic pressures?

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SEVEN
DAY
BOOK